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Experimental Evaluation of Fibrous Bed Coalescers for Separating Oil-Water Emulsions

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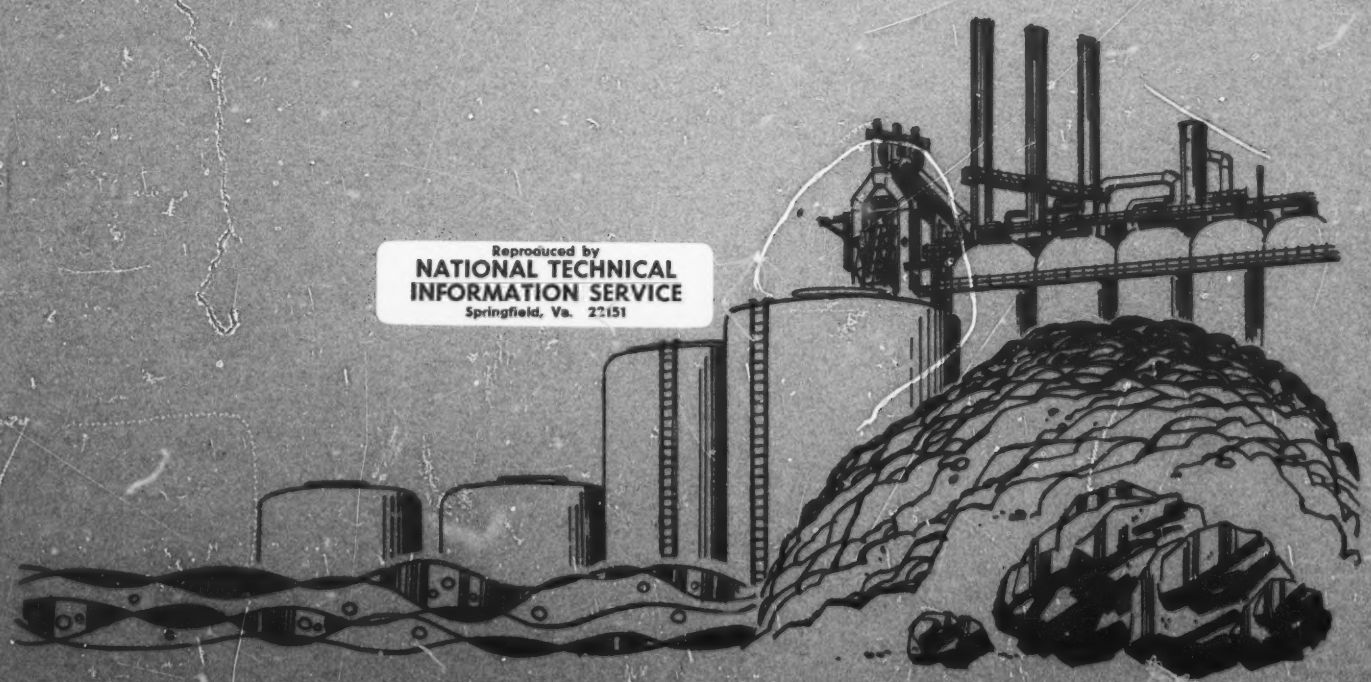

U.S. ENVIRONMENTAL PROTECTION AGENCY

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EXPERIMENTAL EVALUATION OF FIBROUS BED COALESCERS FOR SEPARATING OIL-WATER EMULSIONS

by

Illinois Institute of Technology
Department of Chemical Engineering
Chicago, Illinois 60616

for the

ENVIRONMENTAL PROTECTION AGENCY

INDUSTRIAL POLLUTION CONTROL SECTION
Grant No. 12050 DRC

November 1971

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ABSTRACT

A 1 sq. ft. coalescer unit using filter press construction has been designed for removing dispersed oil from water and tested on both a synthetic stream and on an actual pollutant stream. The oil removal efficiency was essentially 100% at a superficial velocity of 1 fpm. The pressure drop increased from 3 to 25 psi over run times which varied from 13 hrs. to 294 hrs., due to both accumulation of oil in the bed and mechanical degradation of the fibers. Preliminary tests indicated that the bed degradation phenomenon could be eliminated by structurally stabilizing the compressed fibers with methacrylate resin. Such fiber beds could be regenerated by various solvent treatments and reused.

The performance of fiber glass coalescers was studied in depth using a cell with an active area of 1.77 sq. in. The commercial fibers, with phenol formaldehyde coatings and a fiber diameter of 3.2μ gave efficiencies of 90-99% with bed densities of 12 lb./ft.^{3} when operating at superficial velocities from 0.2 to 4 fpm on emulsions containing 50-500 ppm of oil.

The present design is suitable for large scale operation by the use of both multiple cells and larger individual cells. It is estimated that operating costs on the order of 0.13 \$/10^3 gal. are involved for the worst case of single use of fiber. If the fibers can be regenerated c[illegible]ing costs would be reduced to 0.01 \$/10^3 gal.

This report was submitted in fulfillment of Grant No. 12050 DRC between the Environmental Protection Agency and the Illinois Institute of Technology.

CONTENTS

Section		Page
I	Conclusions	1
II	Recommendations	3
III	Description of Large Coalescer	5
IV	Results of Large Coalescer Cell	23
V	Economics of Filter/Coalescer Operation	39
VI	Description of Small Coalescer	43
VII	Results of Small Coalescer Tests	59
VIII	Microscopic Study of Fibrous Bed Coalescer	81
IX	Stabilization Tests	85
X	Acknowledgements	91
XI	References	93
XII	Glossary	95
XIII	Symbols	97

FIGURES

		PAGE
1	GENERAL SCHEMATIC OF THE PLASTIC COALESCER CELL	7
2	FINAL COALESCER UNIT	10
3	COMPLETE CELL IN HORIZONTAL POSITION WITH INFLUENT SIDE ON TOP	11
4	INFLUENT END PLATE PARTIALLY REMOVED, SHOWING TOP SEAL FRAMES	11
5	ENTRANCE SIDE TO DIAPHRAGM ASSEMBLY	11
6	SPECIAL INNER SEAL FRAME	11
7	OIL EFFLUENT FRAME OVER TFE SCREEN SECOND STAGE	12
8	DISASSEMBLY VIEW	12
9	ASSEMBLY VIEW	12
10	TOP PERFORATED PLATE, BOTTOM ASSEMBLED DIAPHRAGM WITH TOP GASKET IN PLACE	12
11	TOP GASKET REMOVED, SHOWING USED DIAPHRAGM. SQUARE LINE AT EDGE IS METAL O-RING SEAL WHICH HAS CUT THROUGH FIBER BLANKETS	13
12	METAL O-RING SEAL AFTER CUT EDGES HAVE BEEN REMOVED	13
13	BOTTOM VIEW: SHOWS BOTTOM GASKET WITH GROOVE FROM METAL O-RING AND SPACER PLATE, ALL RESTING ON BOTTOM PERFORATED PLATE	13
14	VIEW OF TREAD PLATE AND FORMED GASKET ON PERFORATED PLATE	13
15	1/2 IN. OF 3.2μ GLASS, 2 IN. OF 10.1μ GLASS WITH METAL O-RING SEAL ON BOTTOM PERFORATED PLATE AND GASKET. 1/8 IN. SPACER PLATE IN POSITION. NOTE 1/2 IN. AND 5/16 IN. ALIGNMENT PINS	14
16	COMPLETE 5 INCHES OF FIBER GLASS	14

FIGURES (CONTINUED)

		PAGE
17	UPPER GASKET IN PLACE	14
18	UPPER PERFORATED PLATE IN PLACE	14
19	COMPLETE ASSEMBLY BUT NOT BOLTED TOGETHER	15
20	TFE SCREEN BEING INSERTED ABOVE WATER EFFLUENT SPACER FRAME	15
21	OIL EFFLUENT SPACER FRAME	15
22	EFFLUENT SIDE OF DIAPHRAGM ALL ASSEMBLED	15
23	DIAPHRAGM THRU EFFLUENT SIDE ASSEMBLY	16
24	INFLUENT SPACER FRAME	16
25	INFLUENT END PLATE	16
26	COMPLETE ASSEMBLY	16
27A	FIBROUS BED ASSEMBLY	18
27B	SCREEN DETAILS	18
28	TEST ASSEMBLY	20
29	PHOTOGRAPH OF TEST ASSEMBLY	21
30	SUMMARY OF PERFORMANCE CHARACTERISTICS OF 1 SQ. FT. FILTER/COALESCER (SELECTED POINTS)	36
31	SCHEMATIC DIAGRAM OF RECIRCULATING SYSTEM	44
32	SCHEMATIC DIAGRAM OF ONCE-THROUGH SYSTEM	46
33	PHOTOGRAPH OF ONCE-THROUGH SYSTEM	47
34	PHOTOGRAPH OF INLET SECTION ASSEMBLY OF ONCE-THROUGH SYSTEM	47
35	SMALL SCALE COALESCER CELL WITH FIBROUS BED TEST SECTION	49
36	PHOTOGRAPH OF SMALL SCALE COALESCER CELL	50
37	LIGHT TRANSMISSION APPARATUS	54
38	CALIBRATION OF LIGHT TRANSMISSION APPARATUS	56
39	PRESSURE DROP VS SUPERFICIAL VELOCITY FOR SINGLE PHASE FLOW (VOID FRACTION 0.94)	62

FIGURES (CONTINUED)

		PAGE
40	PRESSURE DROP VS SUPERFICIAL VELOCITY FOR SINGLE PHASE FLOW (VOID FRACTION 0.90)	65
41	TIME-DEPENDENT BEHAVIOR OF PRESSURE DROP AT DIFFERENT SUPERFICIAL VELOCITIES FOR BAKELITE COATED FIBER GLASS FIBERS	69
42	COMPARISON OF TIME-DEPENDENT BEHAVIOR OF PRESSURE DROP FOR COATED FIBER GLASS AND UNCOATED GLASS FIBERS	70
43	TIME-DEPENDENT BEHAVIOR OF PRESSURE DROP AT DIFFERENT VELOCITIES FOR 1/1 ILS OIL/KEROSENE DISPERSED IN WATER	71
44	COMPARISON OF TIME-DEPENDENT BEHAVIOR OF PRESSURE DROP FOR ONCE-THROUGH AND RECIRCULATING SYSTEMS	78
45	APPARATUS FOR HIGH SPEED CINEPHOTOMICROGRAPHY	82
46	MICROSCOPIC PICTURES OF OIL DROPS COALESCING IN A FIBROUS BED	83
47	ASSEMBLY FOR STABILIZATION TESTS	86

TABLES

No.		Page
1	Large Scale Coalescer Tests with Double Layer 3.2μ Glass	25
2	Large Scale Coalescer Test. Standard Run at 70°F	27
3	Large Scale Coalescer Tests with Samples from Interlake Steel Corp.	28
4	Large Scale Coalescer Tests with Samples from Interlake Steel Corp.	29
5	Large Scale Coalescer Tests - One Fourth Standard Flow Rate	30
6	Large Scale Coalescer Tests - At Low Temperature	32
7	Large Scale Coalescer Tests - At Standard Conditions	33
8	Summary of Test Results with Aluminum Cell	35
9	Physical Properties of the Fibers	51
10	Physical Properties of the Materials Used	53
11	Calibration of Light Transmission Apparatus	57
12	Single Phase Flow Through Coated Fiber Glass Fibers	60
13	Single Phase Flow Through Coated Fiber Glass Fibers	61
14	Single Phase Flow Through Uncoated Glass Fibers	63
15	Single Phase Flow Through Uncoated Glass Fibers	64
16	Preliminary Investigation of Coalescer Performance	66
17	Coalescer Performance With and Without Regeneration for Coated Fiber Glass Fibers	72
18	Coalescer Performance With Uncoated Glass Fibers and Uncoated Glass Fibers Treated With Various Hydrophobic Coatings	73

No.		Page
19	Time Versus Pressure Drop for Coated Fiber Glass Fibers and Uncoated Glass Fibers	76
20	Coalescer Performance Data for Recirculating System	79
21	Coalescer Performance Data for Once-Through System	80
22	Regeneration Tests on Stabilized Fibers	87

SECTION I
CONCLUSIONS

1. A 1 sq. ft. coalescer cell using filter press construction has been designed and tested on a synthetic oil dispersion and on an actual pollutant stream. It was found to give essentially 100% coalescence efficiency at a flow rate of 7.5 gpm (1 fpm velocity) over the entire run time. The controlling parameter for a practical unit appears to be the life of the bed. This is arbitrarily defined in the present work as the through-put up to the point where the pressure drop reaches 25 psi.

2. The present coalescer design may be used as is and readily scaled up either by using multiple cells or by increasing the area of individual cells. The capacity, corresponding to a pressure drop of 25 psi, for a flow rate of 7.5 gpm was found to be 710 gal. for a stream at 85°F and 100 gal. for a stream at 65°F. These capacities are low but they do not preclude practical operations since it is a simple matter to install new fiber beds.

3. Stabilization of the fibers with regards to the mechanical degradation was accomplished by coating the compressed fibers with isobutyl methacrylate resin. This medium, which showed the same coalescence efficiency and pressure drop characteristics of the original phenol formaldehyde coated fibers, could be regenerated by solvent treatment.

4. Operating costs on the order of 0.13 $\$/10^3$ gal. are involved for the single use of fibers. If the fiber can be regenerated they would drop to 0.01 $\$/10^3$ gal. or lower.

5. The factors controlling the coalescence performance of fiber glass media on secondary emulsions of oil in water have been evaluated in a small scale unit with an area of 1.77 sq.in.

6. Small scale tests have shown that commercially available fibers, 3.2μ diameter and coated with phenol formaldehyde resin which are an effective coalescing medium for secondary oil emulsions, have pressure drop characteristics

which increase continually with time. This increase is probably due both to oil accumulation in the fibers, a reversible phenomenon, and mechanical degradation of the fibers, an irreversible phenomenon.

SECTION II
RECOMMENDATIONS

It is recommended that a demonstration unit be constructed using the final design developed here and evaluated on a selected industrial pollutant stream. It is desirable to use a unit of 25-100 gpm, 1 to 4 $ft.^2$ active area, which will operate on some percentage like 10% of the total stream, to facilitate the necessary experimental changes.

It is recommended that the important parameters which control the coalescence efficiency be further investigated. Probably the most important parameter involves stabilization and regeneration of the fiber medium. In addition the effect of such parameters as the particle-size distribution, zeta potential, media pore size distribution and wettability should be quantitatively related to the coalescence performance. A knowledge of these relationships is essential to minimize upsets which will occur due to the variable nature of any pollutant.

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16. Abstract A laboratory scale coalescer bed was formed from standard, phenol formaldehyde coated fiber glass, consisting of 3 layers: (1) 2 inches of 10.1 micron glass of 0.6 lb/ft^3 density; (2) 1/2, 1 , or 1 1/2 inches of 3.2 micron glass, 0.6 lb/ft^3 density; and (3) 2 inches of 10.1 micron glass, 0.61 lb/ft^3. The bed was then compressed between screens to an overall thickness of 1/4 inch, giving an apparent overall density to the working membrane of 10.1 lb/ft^3. By testing the cell on a synthetic oil dispersion and an actual pollutant stream, a 100% coalescence efficiency at a 7.5 gpm flow rate over the entire run time was established. Capacities, corresponding to a 25 psi pressure drop through the bed, for a 7.5 gpm flow rate were 710 gal for an 85°F waste and 100 gal for a 65°F waste. Stabilization of fibers to mechanical degradation was accomplished by coating the compressed fibers with isobutyl methacrylate resin. This medium, showing the same coalescence efficiency and pressure drop characteristics for the original medium, was regenerable by solvent treatment. Operating costs based on single use of fibers were estimated at 13¢/1000 gal, but successful fiber regeneration would drop the cost to 1¢/1000 gallons or less. (Lowry-Texas)

17a. Descriptors *Oil wastes, *Coalescence, *Fibrous beds, Membrane processes, Resins, Separation techniques, Density, Pressure, Flow rates, Industrial wastes, Dispersion, Laboratory tests, *Waste water treatment

17b. Identifiers *Fiber glass

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SECTION III

DESCRIPTION OF LARGE COALESCER

Introduction

The object of the present program was to design and breadboard on operational coalescer with 1 sq. ft. of active area using filter press construction. Overall design specifications were 1 fpm superficial velocity operating on an influent containing 100 ppm of oil in the form of a secondary emulsion. A practical definition of an emulsion as used in these large scale tests is one formed by passage thru a pump operating at 3450 RPM. The influent oil would be diluted with at least 50% kerosene. The other 50% influent oil being a representative pollutant material obtained from the hot mill cooling water treatment system at Interlake Steel Corporation. No. 30 lube oil was found to give comparable results to the actual pollutant oil and was used in many of the tests.

The coalescer bed was formed from standard, phenol formaldehyde coated fiber glass and consisted of the three layers: a) 2 inches of 10.1μ glass, 0.6 lb./ft.^{3} density, b) 1/2, 1 or 1 1/2 in. of 3.2μ glass, 0.6 lb./ft.^{3} and c) 2 inches of 10.1μ glass 0.6 lb./ft.^{3}. These fibers were Owens Corning "Aerocor", 10.1μ and "FM-004", 3.2μ . The bed, usually with 1/2 in. of 3.2μ glass, was compressed between screens to an overall thickness of 1/4 in. giving an apparent overall density to the working membrane of 10.8 lb./ft.^{3}.

The above design specifications were based on the correlations developed in the first phase work on this project (1) and other work carried out at the Illinois Institute of Technology (2-15). The design characteristics were developed during this second phase by tests in a small scale cell of 1.5 in. dia. which are given in Section VI of this report.

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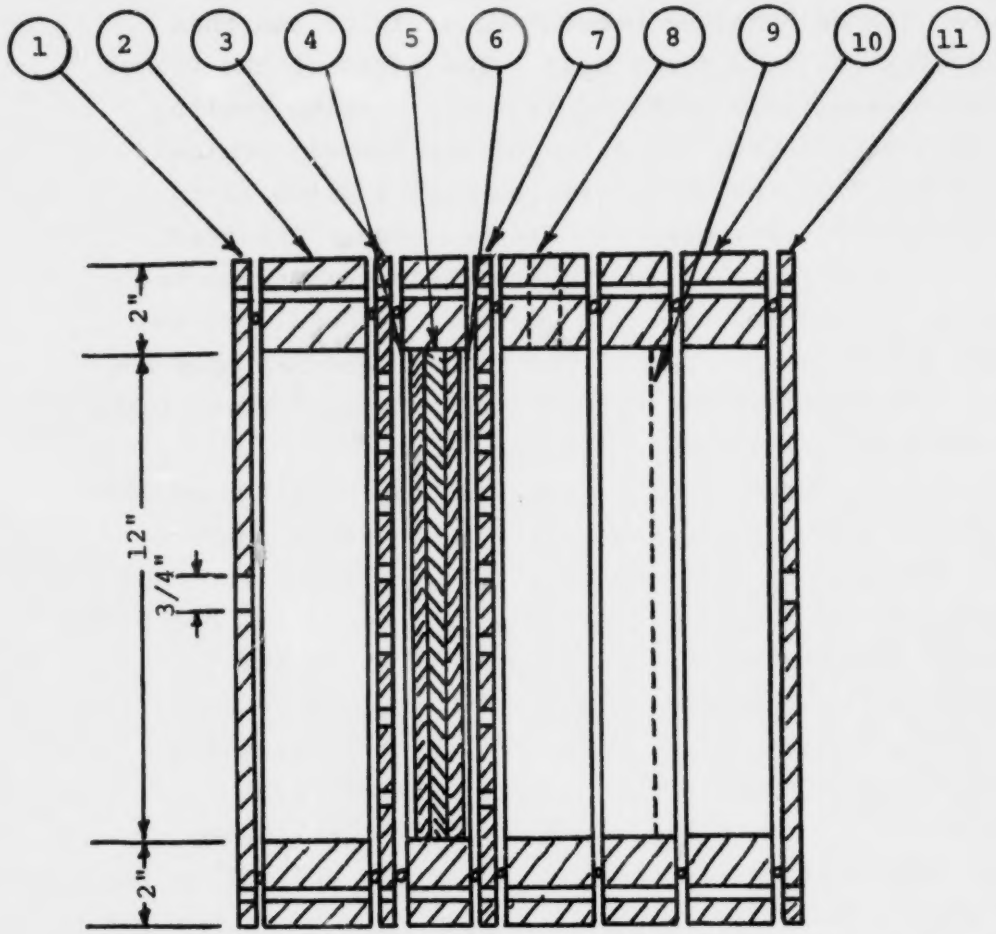
The structural design for large cells was developed in two stages. In the first stage a plastic cell was used to develop an operational model. This plastic construction permitted ideas to be tried out at will with a minimum of effort, expense and machining. While the filter press principal is a very old art, it has not previously been employed in filter/coalescer applications and considerable developmental effort was required to develop a working design. The second stage involved the construction of a metal unit which, with multiple cells, could be used in small scale demonstration unit at rates on the order of 25 to 50 gpm.

General Schematic Cell Description

The cells employed square frames, 16 in. outside square (O.S.) by 12 in. inside square (I.S.). The overall cell consisted of a front (1) and rear (11) end plate, an entrance frame (2), diffuser plates (3) and (7), the coalescer bed (5), some type of support section (4) and (6), oil disengaging frame (8), an oil separating teflon screen (9), and the effluent frame (10). The particular design employed in both stages was selected to allow ease in modifications. Optimum filter press design was not considered in this program. The final design employs a unit cell length (without end plates) of six inches which could be reduced to 2 inches by increasing the structural complexity.

Preliminary Plastic Coalescer Unit

The plastic cell used in the preliminary tests is shown in Figure 1. The cell frames (except for that containing the fiber bed), 16 in., outside square, by 12 inches, inside square, were formed by laminating strips of methyl methacrylate plastic, 14 in. by 2 in. by 1/4 in., to the desired thickness. Laminating lacquer consists of methyl methacrylate monomer with 5% each of benzoyl peroxide catalyst and paramethyl toluidine accelerators, heated to 80°C for approximately 3 minutes so as to form a viscous liquid. The



1. End Plate
2. Entrance Frame
3. Diffuser Plate
4. Screen Support
5. Coalescer Bed
6. Screen Support
7. Diffuser Plate
8. Oil Disengaging Frame
9. 100 Mesh Monel Screen Coated with 0.005 In. Teflon
10. Effluent Frame
11. End Plate

FIGURE 1 GENERAL SCHEMATIC OF PLASTIC COALESCER CELL

lacquer was applied to both surfaces of the lucite strips, which were clamped together between wood strips and then set by heating to 100°C for 1 hour. The edges of the frames were given several seal coats of lacquer. O-ring sealing grooves were milled into the faces of the frames, nominal dimensions for 3/16 in. cross section O-ring being 13 in. inside square, 5/64 in. deep and 1/4 in. wide. The thickness of the individual 1/4 in. lucite strips varied up to 1/32 inches. Minor leaks, which continually developed on bolting up the assembly due to cracking of material, did not interfere with the preliminary test evaluations. These leaks were eliminated in the final design.

The special frame for the fiber bed was constructed with one of the 1/4 in. strips inset 1/2 in. to give a support ledge for the fibrous bed assembly. The fiber bed was held between two, 16 ga. sheets, drilled with 144-1/2 in. holes on 1 in. square centers which were located in the central 11 inch square. The plates with the fiber glass between them (2 in. of 10.1μ, 1/2, 1 or 1 1/2 in. of 3.2μ, and 2 in. of 10.1μ) was compressed to a thickness of 1/4 or 3/16 in. by 1/4 in. bolts spaced on 5-1/2 in. square centers. The assembly was then bolted to the projecting ledge with 12 no. 8 bolts. This plastic assembly in operation had to be mounted horizontally with the flow downward. The upper circumferential edge was sealed by covering with 1 in. strip of electrician's tape which in turn was covered with a strip of silicone putty (John Mansville- Dux Seal).

The TFE screen (9), Figure 1 , was mounted by taking a piece, 13 in. square, bending the edges up 1/2 in. and bolting the edges to the inside of a frame. A seal was obtained by a strip of silicone putty around the edges.

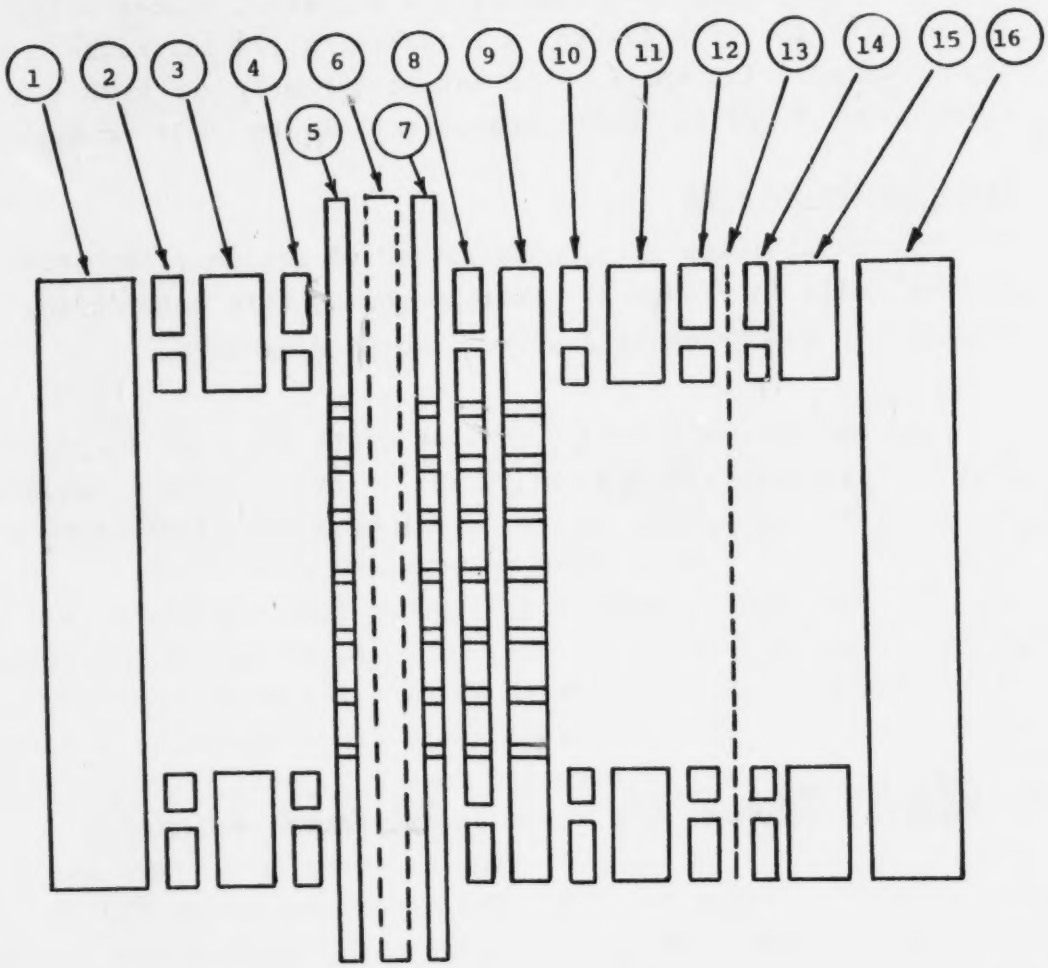
The influent and water effluent streams flow thru 3/4 IPS nozzles in the center line of the end plates. The oil effluent stream leaves thru a 1/2 in. IPS nozzle in the wall of frame (8), Figure 1 .

The end plates consisted of 1/4 in. steel plates stiffened with ribs of 1 1/2 in. x 1 1/2 in. x 1/4 in. angle irons spaced 2 in. apart. The entire assembly was held together by 8-3/8 in. bolts spaced on a 15 in. bolt square.

Final Coalescer Unit

The final large cell, constructed of aluminum, is shown schematically in Figure 2. Photographs of this cell during disassembly and assembly are shown in Figures 3-26.

The end plates (1) and (16) consist of 16 in. x 16 in. x 2 in. plates. The frames (3), (11) and (15) are 16 in. outside square (O.S.) by 12 in. inside square (I.S.) by 1 in. thick sawed from plate stock. Each frame is provided with 4-1/2 in. FPT openings, located 3 1/2 inches from one edge. A support plate (9) is 16 in. O.S. by 1 in. thick and the central 11 in. square area drilled with 144-1/4 in. holes on 1 in. square centers. The various elements are sealed with 1/4 in. O-rings. The O-ring grooves are formed by seal frames, (2), (4), (8), (10), (12), and (14). The inner frames (except (8)) are 13 in. O.S. x 12 in. I.S. and the outer seal frame is 16 in. O.S. x 13 5/8 in. I.S. The inner seal frame (8) is a solid plate with 144-1/4 in. holes which line up with those in the diffuser plate (7) so as to provide support via plate (9). The seal frames are sawed from 1/4 in. plates. All of these pieces are provided with 8-1/2 in. holes on a 15 in. bolt square. The second stage screen barrier (13) consists of a standard 100 mesh monel screen coated with 0.005 in. of TFE.



1. End Plate
2. Seal Frame
3. Entrance Frame
4. Seal Frame
5. Diffuser Tread Plate
6. Coalescer Bed
7. Diffuser Tread Plate
8. Seal Frame
9. Support Plate
10. Seal Frame
11. Oil Effluent Frame
12. Seal Frame
13. 100 Mesh Monel Screen Coated with 0.005 in. Teflon
14. Seal Frame
15. Water Effluent Frame
16. End Plate

FIGURE 2 FINAL COALESCER UNIT

FIGURE 3. COMPLETE CELL IN HORIZONTAL POSITION WITH INFLUENT SIDE ON TOP.

FIGURE 4. INFLUENT END PLATE PARTIALLY REMOVED, SHOWING TOP SEAL FRAMES.

FIGURE 5. ENTRANCE SIDE TO DIAPHRAGM ASSEMBLY.

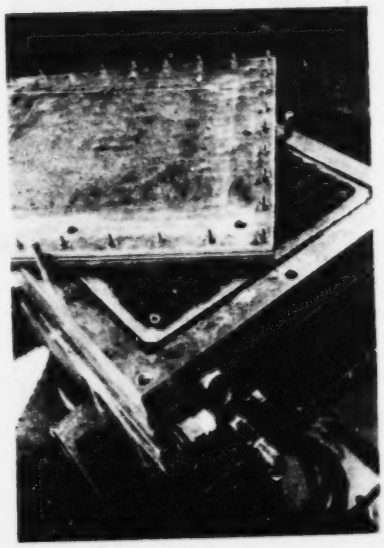


FIGURE 6. SPECIAL INNER SEAL FRAME.

FIGURE 7. OIL EFFLUENT FRAME OVER TFE SCREEN SECOND STAGE.

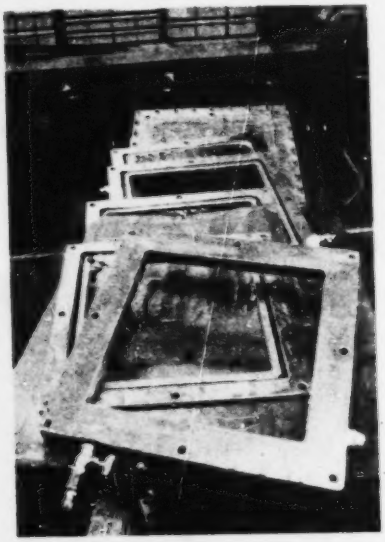


FIGURE 8. DISASSEMBLY VIEW.

FIGURE 9. ASSEMBLY VIEW.

FIGURE 10. TOP PERFORATED PLATE, BOTTOM ASSEMBLED DIAPHRAGM WITH TOP GASKET IN PLACE.

FIGURE 11. TOP GASKET REMOVED SHOWING USED DIAPHRAGM. SQUARE LINE AT EDGE IS METAL O-RING SEAL WHICH HAS CUT THROUGH FIBER BLANKETS.

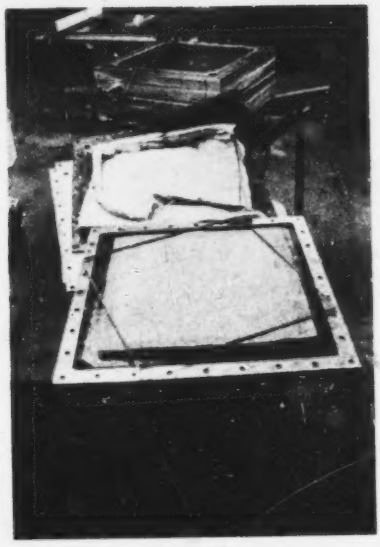


FIGURE 12. METAL O-RING SEAL AFTER CUT EDGES HAVE BEEN REMOVED.

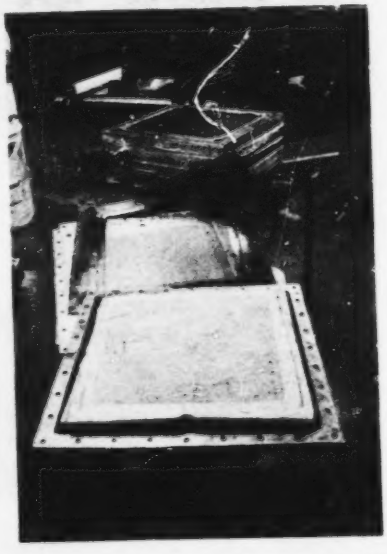


FIGURE 13. BOTTOM VIEW: SHOWS BOTTOM GASKET WITH GROOVE FROM METAL O-RING AND SPACER PLATE, ALL RESTING ON BOTTOM PERFORATED PLATE.

FIGURE 14. VIEW OF TREAD PLATE AND FORMED GASKET ON PERFORATED PLATE.

FIGURE 15. 1/2 IN. OF 3.2u GLASS, 2 IN. OF 10.1u GLASS WITH METAL O-RING SEAL ON BOTTOM PERFORATED PLATE AND GASKET. 1/8 IN. SPACER PLATE IN POSITION. NOTE 1/2 IN. AND 5/16 IN. ALIGNMENT PINS.

FIGURE 16. COMPLETE 5 INCHES OF FIBER GLASS.

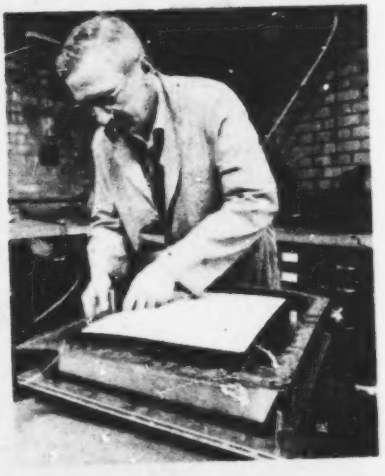


FIGURE 17. UPPER GASKET IN PLACE.

FIGURE 18. UPPER PERFORATED PLATE IN PLACE.

FIGURE 19. COMPLETE ASSEMBLY BUT NOT BOLTED TOGETHER.

FIGURE 20. TFE SCREEN BEING INSERTED ABOVE WATER EFFLUENT SPACER FRAME.

FIGURE 21. OIL EFFLUENT SPACER FRAME.

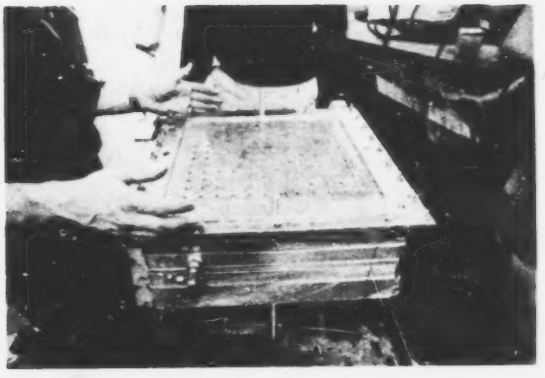


FIGURE 22. EFFLUENT SIDE OF DIAPHRAGM ALL ASSEMBLED.

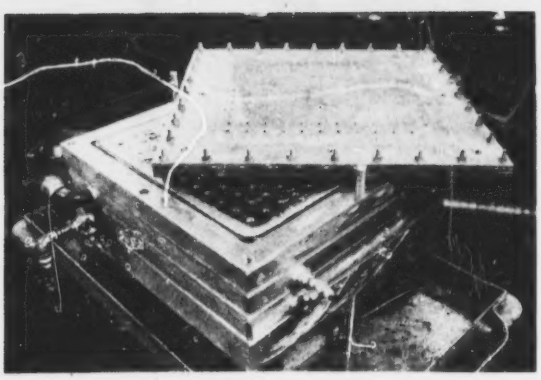


FIGURE 23. DIAPHRAGM THRU EFFLUENT SIDE ASSEMBLY

FIGURE 24. INFLUENT SPACER FRAME.

FIGURE 25. INFLUENT END PLATE.

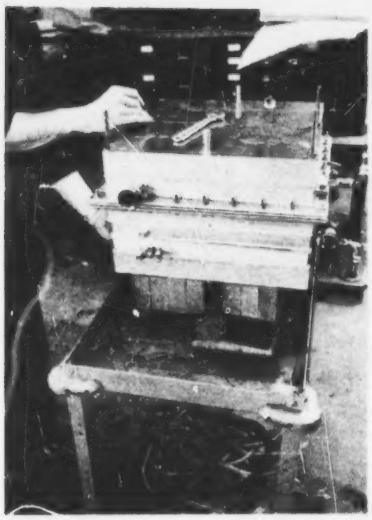


FIGURE 26. COMPLETE ASSEMBLY

The fiber bed assembly is shown schematically in Figure 27A. The fiber glass mats (13), (14), and (15) are clamped between the two perforated plates (3), (8). The screen used is detailed in Figure 27B and has 19% open area. It is probable that the screen details are of little importance since the coarse glass entrance (13) and exit (15) layers act as diffusers. The perforated plates are held in place by the two diffuser plates (1) and (10) which consist of 1/4 in. tread plates (overall thickness 5/16 in.) 18 in. O.S. which are provided with 144-1/4 in. holes on the 11 in. I.S. The space between the treads and the perforated plates are sealed by a urethane rubber gasket (2) and (9). (Devcon Corp., Danvers, Mass., Flexane 85, Liquid Type.) The gasket (approximately 16 in. O.S. by 12 in. I.S.) is formed by casting a strip of urethane between 1/16 in. string guides (thickness of viscous liquid over 1/16 in.), the urethane thickens to a putty within 30 minutes at which time the string guide is removed and the tread plate and perforated plate are clamped together. (See note on indexing below.)

The 1/4 in. overall membrane thickness is maintained by the thickness of the gaskets (4) and (7) and the spacer frame (5). The gaskets are 18 in. O.S. x 12 in. I.S. x 1/16 in. thick and the spacer frame is 18 in. O.S. x 16 in. I.S. x 1/8 in. thick. The membrane thickness can be varied by changing the thickness of either the gaskets or the spacer frame.

The membrane edge is sealed by the metal O-ring (6) which is 1/8 in. cross sectional diameter x 13 1/2 in. I.S.

The fiber glass membrane is composed of 10.1μ glass fibers (nominal density 0.6 lb./ft.^{3}, Owens Corning "Aerocor") and 3.2μ glass fibers (nominal density 0.6 lb./ft.^{3} Owens Corning FM-004).

The diaphragm assembly is drilled with 32-5/16 in. holes on 17 in. bolt square and also 8-1/2 in. holes on 15 in. bolt

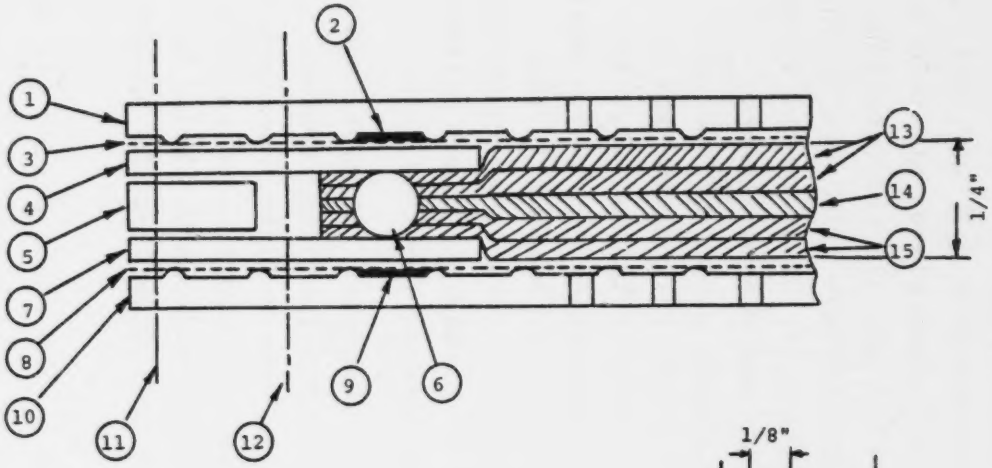


FIGURE 27A FIBROUS BED ASSEMBLY

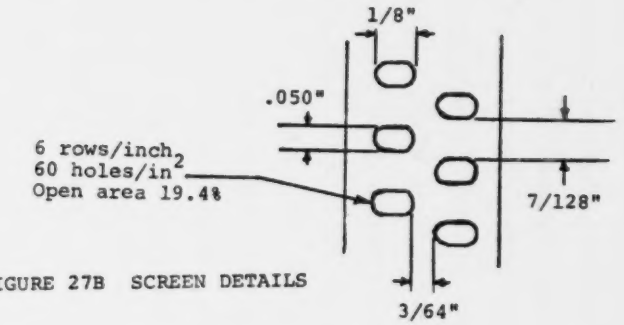


FIGURE 27B SCREEN DETAILS

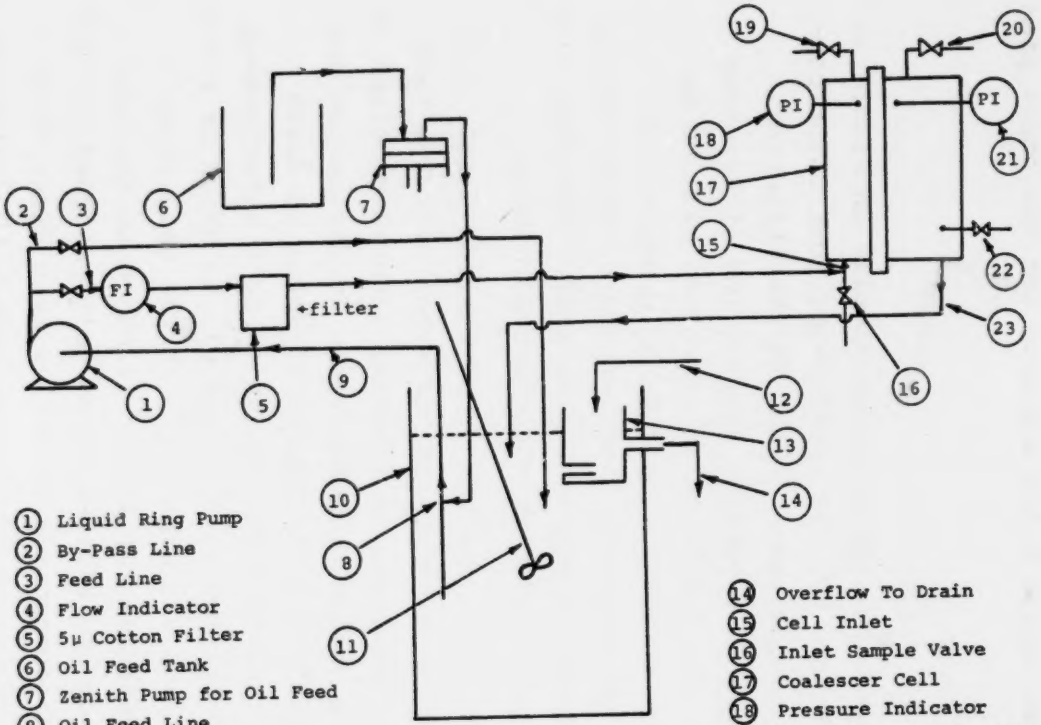
1. Diffuser Tread Plate
2. Urethane Rubber Gasket
3. Screen Support
4. Gasket
5. Spacer Frame
6. Metal O-Ring
7. Gasket
8. Screen Support
9. Urethane Rubber Gasket
10. Diffuser Tread Plate
11. Outside Bolt Square, 8-1/2 in. Diameter Holes
12. Inside Bolt Square, 32-5/16 in. Diameter Holes
13. 10.1μ Coarse Fiber Glass Layer
14. 3.2μ Coarse Fiber Glass Layer
15. 10.1μ Coarse Fiber Glass Layer

square. Two of the 5/16 in. and two of the 1/2 in. holes are used for alignment pining to maintain all pieces, particularly gaskets (2) and (9) within 0.005 in. It was found that only the central 4-5/16 in. holes are needed to pull up the fiber glass bed near 1/4 in. spacing since the final thickness is established when the cell is bolted together through the 1/2 in. holes using 3/8 in. bolts. Only 6 bolts are used since two center holes are used for alignment pins (0.480 in. dia.).

Test Assembly

The test assembly is shown schematically in Figure 28 and pictured in Figure 29. It consists of four major components, mounted on dollies; 1) the filter/coalescer, 2) the feed tank, 3) the pumping system, and 4) kerosene pumping system. Only the final modification will be described here which allows the unit to be operated continuously with a constant oil feed, automatic water makeup and constant temperature via manual control. The flow rate thru the cell is maintained by periodic adjustment.

The feed tank unit consists of a stirred 75 gal. tank (10). Excess water is added to the internal overflow tank (13). The latter automatically adds any necessary volume of makeup water. The system temperature is maintained at any constant value by varying the amount of water to drain (ml./min. to gpm) and thus the amount of cold water makeup. Normally the pump suction is via line (9) to which is added directly the oil feed via line (8). In the case of an actual pollutant stream, the latter is added to the tank put thru the system and effluent from cell returned to tank. Thus the pollutant concentration varies as a first order reaction and may be evaluated over an hour with decreasing inlet concentration rather than in 7 minutes with once through flow. The kerosene solvent which is added to the suction line (9) does not enter the tank or interfere with the evaluation. In preliminary tests oil was added batch-



1. Liquid Ring Pump
2. By-Pass Line
3. Feed Line
4. Flow Indicator
5. 5μ Cotton Filter
6. Oil Feed Tank
7. Zenith Pump for Oil Feed
8. Oil Feed Line
9. Pump Suction Line
10. 75 Gallons Polyethylene Tank
11. Stirrer
12. Makeup Water
13. Internal Overflow Tank
14. Overflow To Drain
15. Cell Inlet
16. Inlet Sample Valve
17. Coalescer Cell
18. Pressure Indicator
19. Oil and Air Vent Valve
20. Oil and Air Vent Valve
21. Pressure Indicator
22. Outlet Sample Valve
23. Cell Effluent

FIGURE 28 TEST ASSEMBLY

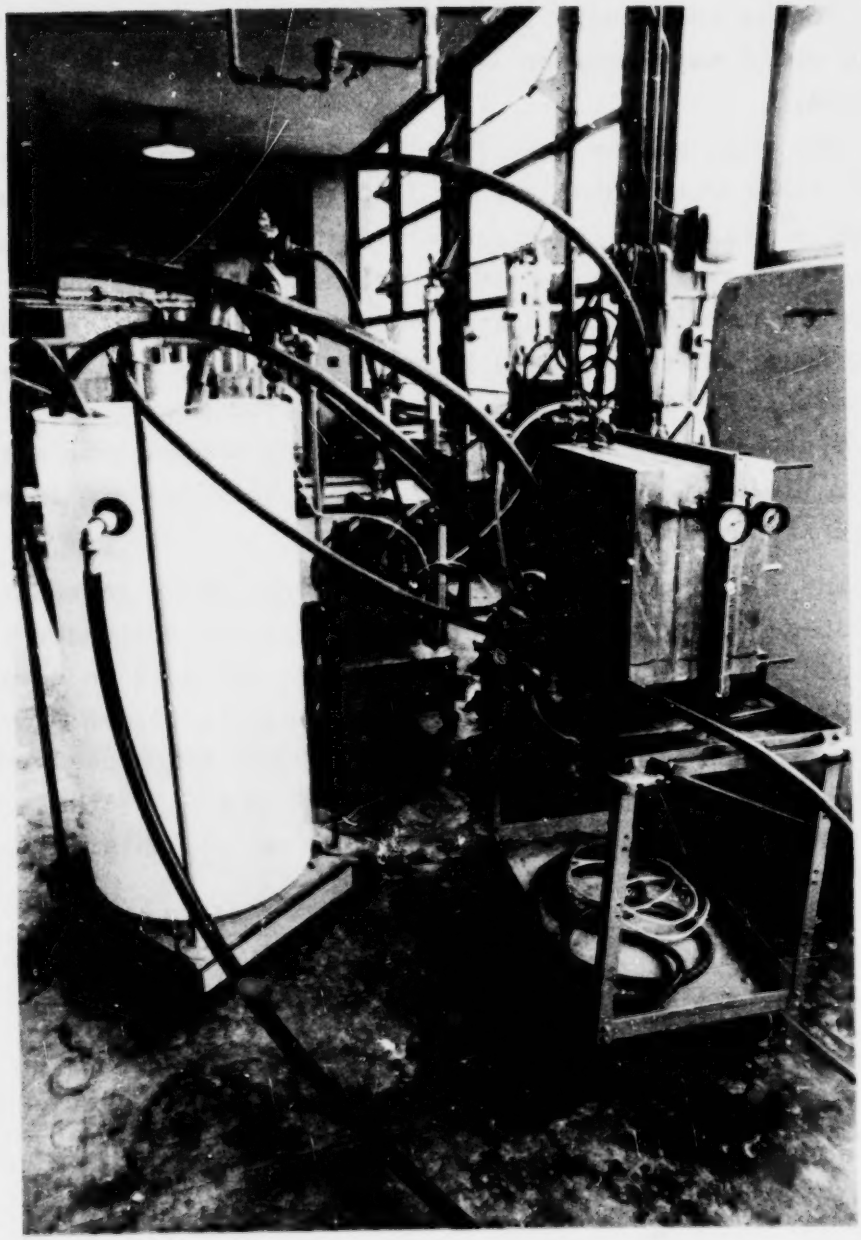


FIGURE 29. PHOTOGRAPH OF TEST ASSEMBLY

wise to the tank every 1/2 hour so that influent concentrations would vary between 100 to 25 ppm or otherwise as desired.

The main system pump (1) is a liquid ring pump (Gould Model 2520) which operates at 3450 RPM giving approximately 25 gpm at 25 psi. Its characteristics of pumping air or water at up to 25 in. vacuum eliminates the problems of pump priming which are present with centrifugal pumps. The oil feed is added by a Zenith pump (7) driven by a variable speed Graham transmission. The oil addition rates (2.2 ml./min. = 85 ppm at 7.5 gpm to coalescer) are adjusted by nudging the setting and by timing the RPM since the Graham settings are insensitive in the low range.

The flow rate is determined by a rotameter (Fischer Porter FP-1-35-G-10/83)float over 6.9 gpm and float for under 6.9 gpm. A filter (Fulflo Model 5μ filter) was used in several tests. Its use was required with the sample of overflow from back wash which otherwise plugged the fiber bed within minutes. Depending upon length of use, the 5μ filter cartridge would coalesce from 50 to 5% of the entering emulsion.

SECTION IV

RESULTS OF LARGE COALESCER TESTS

Preliminary Coalescer Tests

The first tests conducted on the plastic filter coalescer were made at velocities of 0.1 to 0.8 fpm with an influent containing 100-500 ppm of oil. The effluent contained 10-14 ppm when using 1/1 kerosene/#30 oil and 22-33 ppm of 1/1 kerosene/ILS (pollutant oil recovered from the skimming tank at Interlake Steel Corporation). The pressure drop across the diaphragm increased from 3 to 9 psi in two hours for both cases. An attempt to regenerate the bed by passing pure water thru it at high velocity resulted in a diaphragm with essentially zero coalescing ability.

The fiber bed employed in the first tests was maintained by internal bolts between the diffuser plates. Since this bolting technique presents a possible leakage path subsequent tests employed peripherial bolts to eliminate leakage at these points. Tests were made at 0.6 fpm using a diaphragm of 2 in. of 10.1μ , 1 in. of 3.2μ, and 2 in. of 10.1μ glass compressed to approximately 3/16 in. thickness. The influent contained 150 ppm of kerosene plus oil, and the effluent contained no detectable oil. The pressure drop across the diaphragm increased from 2 to 6 psi in two hours.

Final Coalescer Tests

The data for the final large cell are summarized in Table 8 and Figure 30. Run data is tabulated in Tables 1-7. These show that in all runs the effluent stream contained from 0 to 7 ppm of oil with an average of approximately 1 ppm (Table 8). Since readings are generally non-detectable, the high values are probably due to zero point drift in the light transmission equipment (calibration of light transmission apparatus on page 53). These effluent concentrations are independant of the test parameters: thickness and density

of 3.2μ layer (Table 1), velocity through the bed (Table 5), temperature (Table 5B and 6), length of run, and pressure buildup.

The capacity of the coalescer bed, that is, the gallons of influent with 85 ppm of oil that can be passed through to a pressure drop buildup of 25 psi, was found to be 710 gal. for a flow rate of 7.5 gpm (1 fpm velocity) and at temperature of 85°F (Table 7). At 65°F the capacity drops to 100 gal. (Table 6). At flow rate of 1.85 gpm(1/4 fpm velocity) Table 5 , the capacity of the bed was 540 gal. for a temperature of 85°F and 280 gal. for 68°F. Table 3A shows that the effluent from the sand filters can be coalesced effectively. Table 4 shows that the back wash overflow can be coalesced but requires a filter in the line to eliminate plugging of the bed which occurred in the first test with this material. The high turbidity readings of the coalescer effluent are probably due to color bodies since visual inspection did not indicate the presence of any emulsion.

Discussion of Results and Conclusions

The efficiency of the final large cell appears to be essentially 100% under all conditions. The test data show some points with effluent concentrations up to 7 ppm. These are probably due to variations in the analytic method.

The controlling parameter for a practical unit appears to be the life of the bed. This is arbitrarily defined in the present work as the through-put up to the point where the pressure drop reaches 25 psi. The rate of increase in the pressure drop is a function of the flow rate, the amount of oil in the influent, and the temperature of the fluid. The pressure drop has never been observed in our work to stabilize at any value even when subjected to the single phase flow of pure water. Consequently, it appears that the pressure drop is due both to gradual accumulation of oil within the fibers and also mechanical degradation of the fibers. During the coalescing phenomenon some +95% of

TABLE 1*

Large Scale Coalescer Tests With Double Layer 3.2μ Glass

Time hours	Oil Added ml.	Flow Rate $\frac{GPM}{ft^2}$	Velocity fpm	Temp. °F	Pressure Drop psi	Oil ppm **		
						Feed + Tank	Influent + to Bed	Effluent
0	100	7.5	1	-	1.0	75	13	0
1/2	100	7.5	1	-	-	96	41	0
1	100	7.5	1	68	-	29	6	0
1 1/4	100	7.5	1	64	1.8	103	59	0
1 1/2	100	7.5	1	-	-	-	-	-
3 1/2	100	7.5	1	83	4.0	26	13	0
3 1/2	100	7.5	1	80	-	75	54	0
6	100	7.5	1	81	6.0	63	42	0
6 1/2	100	7.5	1	66	7.5	62	53	0
7	100	7.5	1	68	7.5	35	21	0
7 1/4	100	7.5	1	68	7.5	110	77	0
7 3/4	100	7.5	1	72	7.5	13	0	0
8	100	7.5	1	73	7.8	121	81	0
8 1/2	100	7.5	1	75	7.8	28	23	0
9 1/2	100	7.5	1	77	7.8	118	77	0
10	100	7.5	1	78	8.0	25	16	0
11	100	7.5	1	80	8.2	108	70	0
11 1/2	100	7.5	1	82	8.2	24	14	0
12 1/2	100	7.5	1	83	9.0	118	79	0
13	100	7.5	1	84	9.0	21	14	0
	SHUT DOWN OVER NIGHT							
13	100	6.4	0.85	65	12.0	145	95	0
13 1/2	100	6.4	0.85	68	12.0	35	19	0
14	100	6.4	0.85	74	12.5	118	95	0
14 1/2	100	6.4	0.85	78	12.5	31	19	0
	SHUT DOWN OVER NIGHT							

(Continued)

TABLE 1 (Continued)

14 1/2	100	5.6	0.75	56	16.0	63	62	0
15	100	5.5	0.73	-	-	-	-	-
15 1/2	100	5.5	0.73	-	-	-	-	-
16 3/4	100	5.5	0.73	-	-	-	-	-
16 3/4	No more oil - water thru continuously							
18 1/2	0	5.3	0.71	-	16.0	-	-	-
20 1/2	0	5.0	0.67	54	17.0	-	-	-
21	0	5.4	0.72	54	17.0	-	-	-
	Filter Removed							
32	0	5.8	0.77	76	17.0	-	-	-
33	0	5.0	0.67	72	18.0	-	-	-
34	0	4.0	0.53	52	20.0	-	-	-
35	0	3.2	0.43	53	20.0	-	-	-
51	0	1.04	0.14	50	21.5	-	-	-

\+ The 5μ Filter in the line coalesced some of the oil

** By light transmission

* Test conditions tabulated in Table 8

TABLE 2*

Large Scale Coalescer Test. Standard Run at 70°F

Time Hours	Flow Rate GPM/ft²	Velocity fpm	Temp. °F	Pressure Drop psi	Oil ppm** Influent	Oil ppm** Effluent	
	Oil added continuously at 155 ml. per hour						
0	7.5	1	-	1.5	-	-	
1/4	7.5	1	58	2.5	160	0	
1/2	7.5	1	-	3.0	-	-	
3/4	7.5	1	62	3.0	60	0	
1 1/4	7.5	1	65	3.3	-	-	
2 1/4	7.5	1	-	3.8	-	-	
2 3/4	7.5	1	70	3.9	70	0	
6 1/4	7.5	1	70	5.3	75	-	
7 1/4	7.5	1	-	5.7	-	-	
9 3/4	7.5	1	-	7.5	-	-	
11 1/4	7.5	1	-	9.0	-	-	
12 3/4	7.5	1	-	10.0	-	-	
13 1/4	7.5	1	-	10.5	-	-	
18 1/4	7.5	1	70	13.5	83	0	
19	7.5	1	69	17.0	100	-	
19 3/4	7.5	1	68	15.0	-	-	
21 1/2	7.5	1	67	17.0	87	0	
25 3/4	7.4	0.99	-	19.5	-	-	
26 3/4	7.3	0.97	73	19.8	85	0	End
30 1/4	6.4	0.85	-	19.0			
33 3/4	6.1	0.81	-	21.3			
35 1/4	6.1	0.81	-	21.5			
36 3/4	6.0	0.80	-	21.8			
45 1/2	4.9	0.65	-	22.0			
46 3/4	4.9	0.65	-	22.5			

** By light transmission
* See Table 8 for details

TABLE 3*

Large Scale Coalescer Tests With Samples from Interlake Steel Corp.

Note: Samples consisted of 55 gal. The cell effluent was recycled back to the system tank rather than running once through. This permitted the run to be extended over a longer period with a continually decreasing (1st order) oil concentration in the tank. The solvent kerosene was added to the pump suction at the rate of 2.2 ml. per min.

Time Min.	Flow Rate $\frac{GPM}{ft^2}$	Velocity fpm	Temp. °F	Pressure Drop, psi	Oil Concentration TU**		
					Tank	Influent	Effluent
Run 3A	Effluent from sand filters						
0	7.5	1	79	1.0	29	-	5
15	Kerosene added continuously					30	-
17	7.5	1	-	2.0	-	40	-
20	7.5	1	-	2.5	20	41	3.5
32	7.5	1	-	4.5	10	22	2.0
38	7.5	1	82	6.0	12	20	2.0
Run 3B	Overflow liquid from the backwash clarifier						
38	No kerosene added						
38	7.5	1	-	-	-	-	-
40	Started through with kerosene						
41	7.5	1	78	8.5	25	47	3
47	~2.0	0.27	-	25.0	-	-	-
49	0.0	0	-	25.0	-	-	-

** Read by Hach Turbidimeter

* See Table 8 for details

TABLE 4*

Large Scale Coalescer Tests with Samples from Interlake Steel Corp.

Note: Placed 5μ filter before coalescer bed.

Time min.	Flow Rate $\frac{GPM}{ft^2}$	Velocity fpm	Temp. °F	Pressure Drop psi	Oil Concentration TU***		
					Tank	Influent to bed	Effluent
0	No kerosene added						
4	7.5	1	-	1.5	27	12	6.8**
6	Kerosene added at 2.2 ml. per min.						
9	7.5	1	-	-	-	10	-
10	7.5	1	-	-	-	9	6.0
10	Kerosene added at 5.5 ml. per min.						
13	7.5	1	76	2.9	12	10	-
17	7.5	1	-	3.8	-	-	4.5
19	7.5	1	-	4.2	13	-	-
22	7.5	1	-	-	-	-	4.0
23	7.5	1	-	-	6	14	-
29	7.5	1	-	-	-	15	4.0
37	7.5	1	80	7.0	4	18	3.0

*** By Hach Turbidimeter

** Color bodies in the material are probably responsible for these readings

* See Table 8 for details

TABLE 5*

Large Scale Coalescer Tests - One Fourth Standard Flow Rate

Time Hrs.	Velocity fpm	Flow Rate $\frac{GPM}{ft^2}$	Temp. °F	Pressure Drop psi	TU**		ppm***	
					Influent	Effluent	Influent	Effluent
Run 5A	High temperature							
0.0	1/4	1.85	-	($17"H_2O$)	-	-	-	-
0.25	1/4	1.85	-	($30"H_2O$)	-	-	-	-
0.5	1/4	1.85	66	0.5	-	-	102.0	0.0
1.0	1/4	1.85	-	1.30	-	-	-	-
1.5	1/4	1.85	72	1.30	44.0	0.45	125.0	0.0
2.0	1/4	1.85	72	1.40	31.0	0.35	107.0	0.0
3.0	1/4	1.85	80	1.50	85.0	0.34	187.0	0.0
3.5	1/4	1.85	78	1.50	20.0	0.35	97.0	0.0
5.5	1/4	1.85	-	1.60	-	-	-	-
6.5	1/4	1.85	84	1.60	11.0	0.30	67.0	0.0
7.0	1/4	1.85	84	1.60	17.0	0.32	90.0	0.0
8.5	1/4	1.85	88	-	18.0	0.30	95.0	0.0
9.5	1/4	1.85	88	1.70	16.0	0.28	85.0	0.0
10.5	1/4	1.85	84	1.75	15.0	0.28	83.0	0.0
12.0	1/4	1.85	87	1.87	15.0	0.28	83.0	0.0
13.0	1/4	1.85	78	2.20	17.0	0.31	90.0	0.0
14.0	1/4	1.85	81	2.25	15.0	0.31	83.0	0.0
24.0	1/4	1.85	91	3.20	16.0	0.39	95.0	0.0
25.0	1/4	1.85	84	3.35	16.0	0.45	90.0	0.0
27.0	1/4	1.85	88	3.50	16.0	0.70	83.0	2.0
30.0	1/4	1.85	89	3.90	15.0	0.71	85.0	2.0
32.0	1/4	1.85	77	4.60	16.0	0.95	87.0	4.0
34.0	1/4	1.85	83	4.45	16.0	0.96	90.0	4.0
36.0	1/4	1.85	86	4.70	17.0	0.96	90.0	4.0
38.0	1/4	1.85	86	4.75	16.0	0.86	87.0	5.0
45.0	1/4	1.85	87	5.20	16.0	0.91	90.0	4.0

TABLE 5* (continued)

47.0	1/4	1.85	88	5.40	16.0	0.93	87.0	3.0
49.0	1/4	1.85	90	5.45	17.0	0.95	90.0	5.0
51.0	1/4	1.85	81	5.80	17.0	1.10	90.0	5.0
54.0	1/4	1.85	85	5.70	17.0	1.10	90.0	5.0
56.0	1/4	1.85	86	5.80	17.0	1.00	90.0	4.0
58.5	1/4	1.85	88	6.00	17.0	1.00	97.0	4.0
60.0	1/4	1.85	83	6.20	15.0	0.99	90.0	4.0
68.0	1/4	1.85	88	6.60	17.0	0.95	81.0	3.0
71.0	1/4	1.85	94	6.85	17.0	0.60	80.0	2.0
73.0	1/4	1.85	84	7.00	17.0	1.40	83.0	7.0
75.0	1/4	1.85	90	6.90	16.0	1.20	83.0	6.0
78.0	1/4	1.85	89	7.10	16.0	1.10	87.0	5.0
80.0	1/4	1.85	91	7.25	17.0	0.90	87.0	4.0
83.0	1/4	1.85	88	7.50	17.0	1.10	87.0	3.0
93.5	1/4	1.85	97	8.60	18.0	0.56	83.0	4.0
95.0	1/4	1.85	86	8.40	16.0	0.96	83.0	7.0
97.0	1/4	1.85	95	8.30	16.0	0.94	87.0	4.0
Run 5B Low temperature								
99.0	1/4	1.85	68	10.00	16.0	0.36	83.0	0.0
103.0	1/4	1.85	69	11.50	19.0	0.39	92.0	1.0
104.0	1/4	1.85	67	12.00	17.0	0.26	87.0	0.0
106.0	1/4	1.85	68	13.60	16.0	0.25	87.0	0.0
107.0	1/4	1.85	68	14.00	17.0	0.28	90.0	0.0
108.0	1/4	1.85	69	14.50	16.0	0.22	87.0	0.0
109.0	1/4	1.85	68	15.00	16.0	0.25	85.0	0.0
117.0	1/4	1.85	68	16.20	17.0	0.21	83.0	1.0
119.0	1/4	1.85	69	18.80	16.0	0.23	85.0	0.0
120.0	1/4	1.85	68	19.30	17.0	0.25	87.0	0.0
121.0	1/4	1.85	68	19.80	16.0	0.23	87.0	0.0

*** By light transmission

** By Hach turbidimeter

* See Table 8 for details

TABLE 6*

Large Scale Coalescer Tests - At Low Temperature

Time Hrs.	Flow Rate GPM/ft²	Velocity fpm	Temp. °F	Pressure Drop psi			TU **		ppm ***	
				P_1	P_2	ΔP	Influent	Effluent	Influent	Effluent
0.00	7.5	1	-	1.75	0.75	1.00		-	-	-
0.25	7.5	1	69	2.40	0.75	1.65	18.0	0.20	81.0	0.0
0.50	7.5	1	69	3.10	0.75	2.35	18.0	0.27	80.0	1.0
1.00	7.5	1	64	4.00	0,75	3.25	18.0	0.16	85.0	1.0
1.30	7.5	1	66	4.90	0.75	4.15	17.0	0.19	85.0	0.0
2.00	7.5	1	65	5.60	0.75	4.85	18.0	0.16	85.0	0.0
2.30	7.5	1	-	6.25	0.75	5.50		-	-	-
3.00	7.5	1	64	6.90	0.75	6.15	20.0	0.20	85.0	0.0
3.30	7.5	1	64	7.60	0.75	6.85	18.0	0.22	83.0	0.0
4.00	7.5	1	64	8.40	0.75	7.65	20.0	0.30	85.0	0.0
4.30	7.5	1	63	9.20	0.75	8.45	20.0	0.31	85.0	0.0
5.00	7.5	1	64	10.10	0.75	9.35	18.0	0.32	83.0	0.0
6.00	7.5	1	64	12.10	0.80	11.30	18.0	0.26	83.0	0.0
7.00	7.5	1	64	14.15	0.80	13.35	20.0	0.30	83.0	0.0
8.00	7.5	1	63	16.00	0.80	15.20	19.0	0.27	85.0	1.0
9.00	7.5	1	65	18.20	0.90	17.30	23.0	0.32	85.0	3.0
10.00	7.5	1	65	19.50	0.75	18.75	20.0	0.30	85.0	2.0

*** By light transmission

** By Hach turbidimeter

* See Table 8 for details

TABLE 7*

Large Scale Coalescer Tests - At Standard Conditions

Time Hrs.	Flow Rate GPM/ft^2	Velocity fpm	Temp. °F	Pressure Drop psi	TU**		ppm***	
					Influent	Effluent	Influent	Effluent
0.00	7.5	1	-	0.75	-	-	-	-
0.25	7.5	1	91	1.25	19.0	0.25	83	0.0
0.50	7.5	1	90	1.60	18.0	0.22	85	0.0
0.75	7.5	1	85	1.70	18.0	0.20	85	0.0
1.00	7.5	1	85	1.90	17.0	0.18	81	0.0
1.30	7.5	1	88	2.15	18.0	0.20	85	0.0
2.00	7.5	1	88	2.35	19.0	0.25	85	1.0
3.00	7.5	1	88	2.60	18.0	0.25	83	0.0
4.00	7.5	1	87	2.80	19.0	0.26	85	0.0
5.00	7.5	1	87	3.00	20.0	0.28	83	1.0
6.00	7.5	1	84	3.20	19.0	0.23	85	0.0
13.00	7.5	1	84	4.40	18.0	0.25	83	0.0
14.00	7.5	1	84	4.50	19.0	0.26	85	0.0
15.00	7.5	1	84	4.60	20.0	0.24	85	2.0
17.00	7.5	1	-	4.80	-	-	-	-
19.00	7.5	1	84	5.00	18.0	0.25	83	1.0
21.00	7.5	1	86	5.30	19.0	0.27	85	1.0
23.00	7.5	1	86	5.55	19.0	0.25	85	1.0
24.00	7.5	1	88	5.70	20.0	0.22	83	1.0
26.00	7.5	1	87	5.90	19.0	0.20	85	1.0
28.00	7.5	1	84	6.20	20.0	0.19	85	2.0
30.00	7.5	1	85	6.55	18.0	0.18	83	1.0
37.50	7.5	1	84	8.00	20.0	0.20	85	2.0
42.50	7.5	1	87	8.90	20.0	0.18	85	1.0
44.00	7.5	1	86	9.20	19.0	0.20	83	1.0
45.00	7.5	1	84	9.35	20.0	0.22	85	1.0
46.00	7.5	1	86	9.60	20.0	0.18	87	2.0
47.00	7.5	1	90	9.80	20.0	0.18	85	1.0

TABLE 7* (continued)

48.00	7.5	1	86	10.25	19.0	0.25	85	2.0
49.00	7.5	1	80	11.10	20.0	0.21	85	1.0
50.00	7.5	1	82	11.00	18.0	0.20	83	1.0
51.00	7.5	1	84	11.30	20.0	0.25	85	2.0
52.00	7.5	1	84	11.60	19.0	0.25	85	2.0
53.00	7.5	1	84	11.90	19.0	0.24	85	1.0
59.00	7.5	1	88	14.40	22.0	0.25	87	2.0
68.00	7.5	1	88	17.70	20.0	0.28	85	2.0
68.50	7.5	1	88	17.90	21.0	0.30	85	2.0

*** By light transmission

** By Hach turbidimeter

* See Table 8 for details

TABLE 8

Summary of Test Results with Aluminum Cell

Run No.	Oil	Inches[1] Uncom. Fibers 10.1μ/ 3.2μ/10.1μ	Compressed[2] Density lb/ft^3	Flow Rate GPM	Temp. °F.	Pressure Drop vs. Time psi	hrs.	At ΔP=25 psi gal.[3]	hrs.	Tank	Influent	Effluent	Remarks
1	K/#30	2/1/2	12.0	7.5	~80	9.0	22.5	415	56	-	13-80*	0*	with 5μ filter
2	K/#30	2/½/2	10.8	7.5	~70	19.5	26.0	210	28	-	85*	0*	
3A	K/P ***	2/½/2	10.8	7.5	~80	6.0	1/2	-	-	29-12**	40-20**	0*	ILS[4] sand filter
3B	K/P	2/½/2	10.8	7.5	-	-	1/6	-	-	30-20**	47-30**	0*	ILS back wash overflow
4	K/P	2/½/2	10.8	7.5	~80	7.0	2/3	-	-	27-13**	10*	0*	ILS back wash overflow with 5μ filter
5A	K	2/½/2	10.8	1.85	~85	8.3	97	540	294	85*	85*	3*	
5B	K	2/½/2	10.8	1.85	68	19.8	121	(280)	(152)	85*	85*	3*	Excess cooling water
6	K	2/½/2	10.8	7.5	64	18.8	10	100	13	85*	85*	3*	
7	K	2/½/2	10.8	7.50	85	17.9	68.5	710	96	85*	-	2*	

1 Nominal thickness, in. of 10.1μ / 3.2μ / 10.1μ fibers
2 Compressed density in lb/ft^3
3 Extrapolation by linear ratioing last point
4 Sample of pollutant stream from Interlake Steel Corp.

* ppm
** T U
*** P stands for pollutant

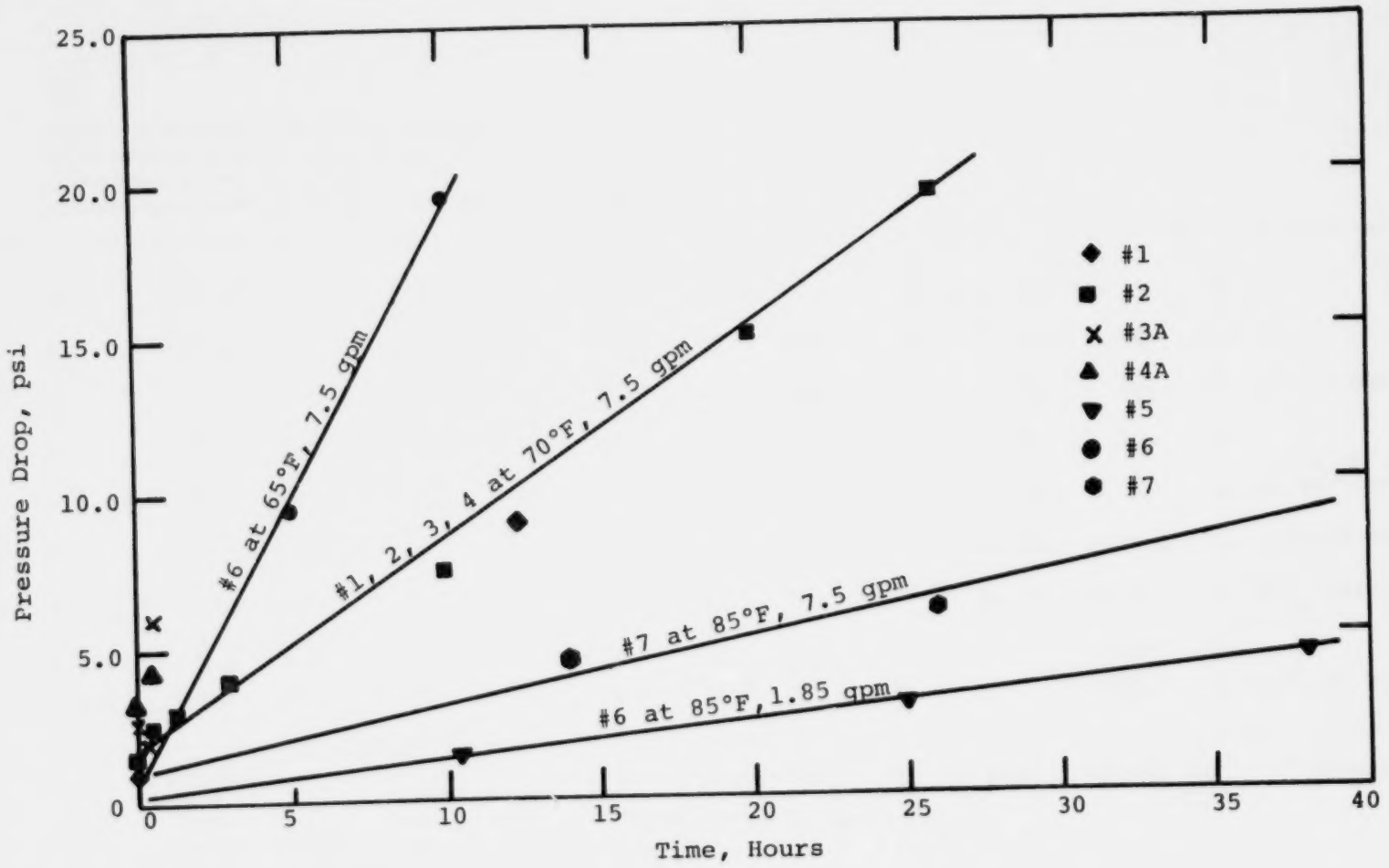


FIGURE 30 SUMMARY OF PERFORMANCE CHARACTERISTICS OF 1 SQ. FT. FILTER/COALESCER (SELECTED POINTS)

coalesced oil passes through the bed. The rate of degradation does not appear to be a function of the actual pressure drop. Abrupt increases occur if the runs are not continuous. Previous work on removal of the oil held up in the used beds by regeneration treatments, such as solvent extraction, usually resulted in a bed with poor coalescence efficiency. Treatments with fiber lubricants, which made the surface more hydrophobic, were unsuccessful in stabilizing the beds. Recently (see Stabilization Test Section) a small bed 1/2 in. effective diameter, was treated with 10% isobutyl methacrylate resin in methylene chloride. This bed gave ∿100% coalescence effectiveness and similar pressure buildup as the regular large cell. Treatment of this used bed with hexane or methanol solvent to remove the oil restored the bed to the original characteristics of low pressure drop and 100% coalescer effectiveness found in unused fibers.

SECTION V

ECONOMICS OF FILTER/COALESCER OPERATION

We have made rough estimates of treatment costs for worst case conditions of 910 gal/ft.^{2} at 85°C which correspond to results from actual tests on fiber as received from manufacturer. Preliminary tests indicate the fibers can be stabilized and the medium regenerated. If so, medium life could be extended many fold, such as 10 or 100 times. Under these conditions the cost of fibers and labor would decrease proportionally. Likewise the heating cost could be eliminated.

1. Fiber glass filter bed

a) Material cost: At the moment the replacement cost of the fine glass membrane is the controlling cost since at 7.5 gpm and 85°F we get 710 gal. thru when ΔP reaches 25 psi. Preliminary tests indicate that this membrane can be regenerated and thus the life (before compression) will be some multiple of this. The actual life will depend on the efficiency of the filter and the nature of the stream being processed, i.e. the dirt which leaks thru and plugs the fine glass.

The bed consists of 2 in. of coarse glass, 1/2 in. of fine glass and 2 in. of coarse glass.

Only the fine glass layer would have to be replaced at present due to fiber migration.

Cost of fine glass in $\$/10^3$ gal. of effluent

1. 1/2 in. layer $\$57.00/10^3 ft^2$.
2. Cells 4 ft. x 4 ft. with 3.5 ft. x 3.5 ft. active area
3. $\$/10^3$ gal. $= \frac{(57)}{(10^3)} \left(\frac{4^2}{3.5^2} \right) \frac{10^3}{710} = 0.10$

b) Labor Costs: The labor cost with a modern automated filter press, for standard operating and change over is minimal. Again change over will constitute over 90% of the cost. Assuming a large unit - 100 cells, each 42 in. x 42 in. active

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area, the actual time to change the pink layer would vary from 1 minute down to 10 seconds. The shut down and start up times of 10 to 20 minutes per cell can be neglected. Using labor costs of 5.75 $/hr. and supervision of 50% of labor (treatment of waste water - waste oil mixtures, US D1, FWPCA 12010 EZV 02/70 May 1970 p. 81) and 1 min. per overall labor burden per all.

$$\frac{(5.75)(1.5)}{(60)} \quad \frac{(1)}{(3.5)^2} \quad \frac{10^3}{710} = .016 \ \$/10^3 \text{ gal.}$$

2. Pumping Costs

$P_{average}$ equals 15 psi (.5 to 25). Using 0.01 $/KWH, 75% overall efficiency of large system, the ocst calculation is:

$$\left(\frac{7.5}{7.48}\right)(15)(144)\left(\frac{1}{60}\right)\frac{0.746}{(550)(.75)} = 0.067 \text{ KW/ft.}^2 \text{ area.}$$

$$\frac{\text{gpm}}{\text{gal./ft.}^3} \quad \text{psi} \quad \left(\frac{\text{in.}^2}{\text{ft.}^2}\right) \quad \frac{\text{min.}}{\text{sec.}} \quad \frac{\text{KW/HP}}{\left(\frac{\text{ft.}^3/\text{sec.}}{\text{HP}}\right)(\text{eff})}$$

$$(0.01)(0.067)\left(\frac{1000}{7.5}\right)\left(\frac{1}{60}\right) = .0016 \ \$/10^3 \text{ gal.}$$

$$(\$/\text{KWH}) \ \frac{\text{KW}}{\text{ft.}^2} \quad \frac{10^3 \text{gal.}}{\text{gpm}} \quad \frac{\text{hr.}}{\text{min.}}$$

3. Heating Cost

Assume that the effluent is at 60°F and must be maintained at 85°F using heat exchanger with 90% heat recovery and heat at $1/10^6$ Btu.

$$(10^3 \text{gal.})(8.33)(85-60)\left(\frac{(1.0)(0.10)}{10^6}\right) = .0125 \ \$/10^3 \text{ gal.}$$

4. Capitol Costs

Direct quotation on 42 in. iron frame 100 units, 2100 ft^2 and completely automated is $50,000.

Cost/$ft.^2$ = 50,000/2100 = 24 \$/$ft.^2$

Installation at 30% give (1.3)(24) = 31 \$/$ft.^2$

Using straight line amortization over 10 years and a 90% stream factor this capitol cost can be calculated (neglecting land, buildings, other special accessories such as heat exchangers).

gal./$ft.^2$/10 years = (7.5)(60)(24)(356)(.9)(10) = 35.4×10^6 gal.

$$\text{dep}/10^3 \text{ gal.} = \frac{31 \times 10^3}{35.4 \times 10^6} = .0009 \text{ \$}/10^3 \text{ gal.}$$

5. Summary

The cost in \$/10^3 gal. are summarized in the table below.

Fiber	0.10
Pumps	0.002
Labor	0.016
Heating	0.013
Filter coalescer	.0009
=	0.13

SECTION VI

DESCRIPTION OF SMALL COALESCER

Experiments were carried out to determine the degree of separation in the small coalescer cell together with the settler.

Recirculating System

Figure 31 is the schematic diagram of the apparatus used in this study. The emulsion was made in a 6 liter baffled stainless steel mixing tank (1) using a model F Lightnin Laboratory mixer (2) which had a 2-inch impeller and speeds could be varied from 800 to 1600 rpm but experiments were run at 1600 rpm. The agitator speed was measured with a stroboscope. A cooling coil (3) made from 3/8 O.D. copper tubing was put into the tank to maintain the constant temperature of the emulsion by controlling the circulation of tap water. A Jabsco 1725 rpm rubber paddle pump (4) was used to circulate the emulsion through the system. Before the emulsion went into the system, it passed through a two liter settler (5) where entrained air was removed. A standoff pipe (6) at the top of the settler allowed separation and removal of the air. It is essential to remove all entrained air before proceeding to the optical cell of light transmission device. After passing through the settler, the emulsion was metered through one of the two rotameters, (7). After metering, the emulsion passed through the inlet optical cell (8) of the light transmission apparatus, then through the fibrous bed (9) where it coalesced. The separated oil stream before the teflon coated screen, and resulting emulsion after passing through the teflon coated screen and outlet optical cell (10) was returned to the baffled mixing tank. For some runs instead of teflon coated screen a 2 liter settler (11) in series with coalescer cell was used to separate coalesced oil. The pressure drop across the fibrous bed was measured at the

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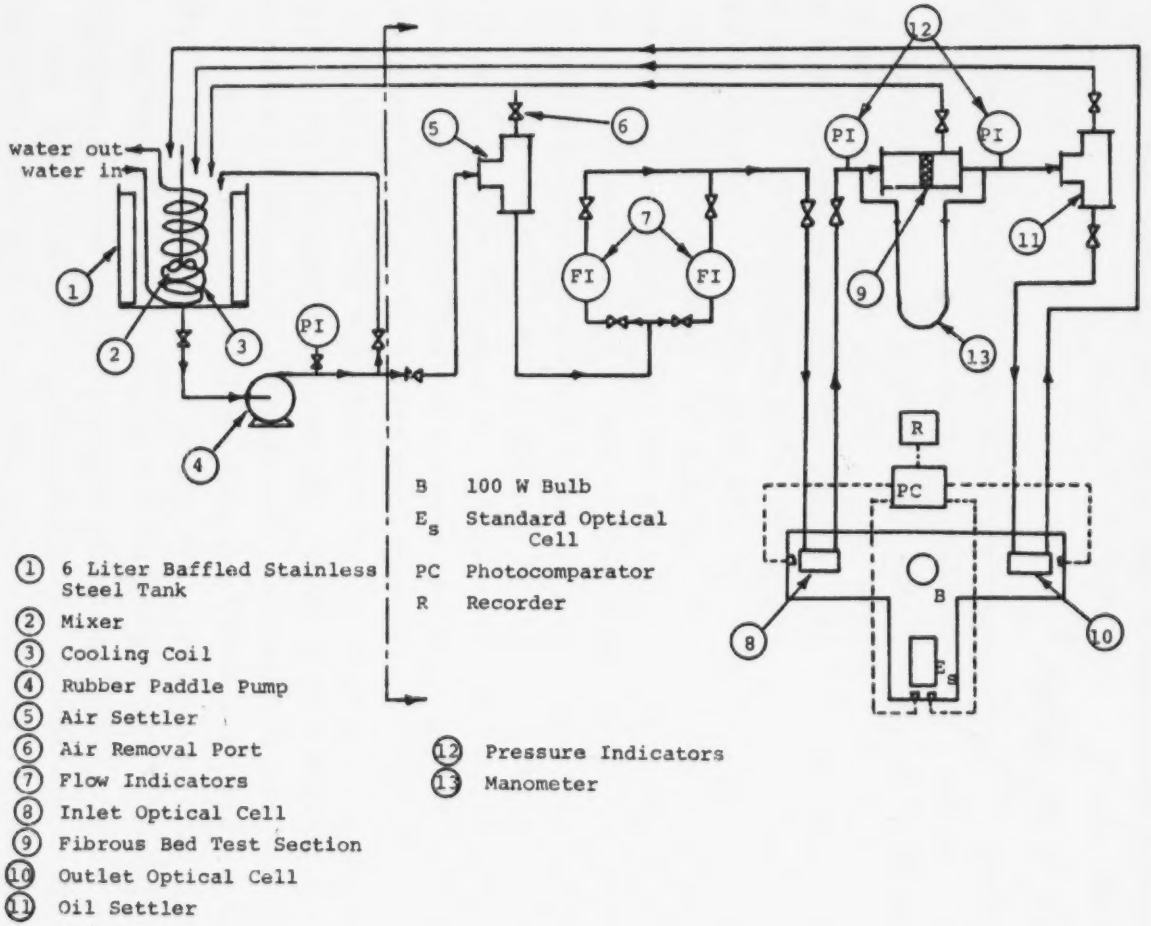


FIGURE 31 SCHEMATIC DIAGRAM OF RECIRCULATING SYSTEM

inlet and outlet of the cell by pressure gages (12) or by a mercury manometer (13).

The recirculating system has several disadvantages: there is a change in inlet drop size distribution with time because of the mixing of streams with different drop size distributions and the inlet oil concentration cannot be kept constant, due to the oil holdup without adding fresh oil in the mixing tank. A once-through system was constructed later to overcome these disadvantages.

Once-through System

Figure 32 is the schematic diagram and Figure 33 is the photograph of the apparatus used. The emulsion was made in a 30 gallon stainless steel tank (1) by recycling the oil/water mixture through the by-pass line. A glass fiber filter (2) could be valved into the by-pass line to remove particulate matter present in the water. The filter was employed prior to making up the emulsion. To control the temperature a heat exchanger (3) was installed between the centrifugal pump (4) and by-pass filter assembly. This assembly is shown in Figure 34. The remaining part of the system was essentially the same, shown on the right of the centerline in Figure 31, as that used in recirculating system except that the effluent from the cell, settler and the optical cell was discharged into the drain.

Coalescer Cell

The coalescer cell is shown in Figure 35 and its photograph in Figure 36. The cell consists of an external 2 1/2 in. O.D. x 6 in. Plexiglas tube (6). Inside the outer tubes are placed three retainer Plexiglas tubes (1) which are sealed by 1/8 in. O-rings. Four 1/8 in. mesh wire screens (2) were used to hold the bed between the center and the inlet retainer tubes. A 100 mesh teflon coated screen (5) was held between center and outlet retainer tubes. The Plexiglas

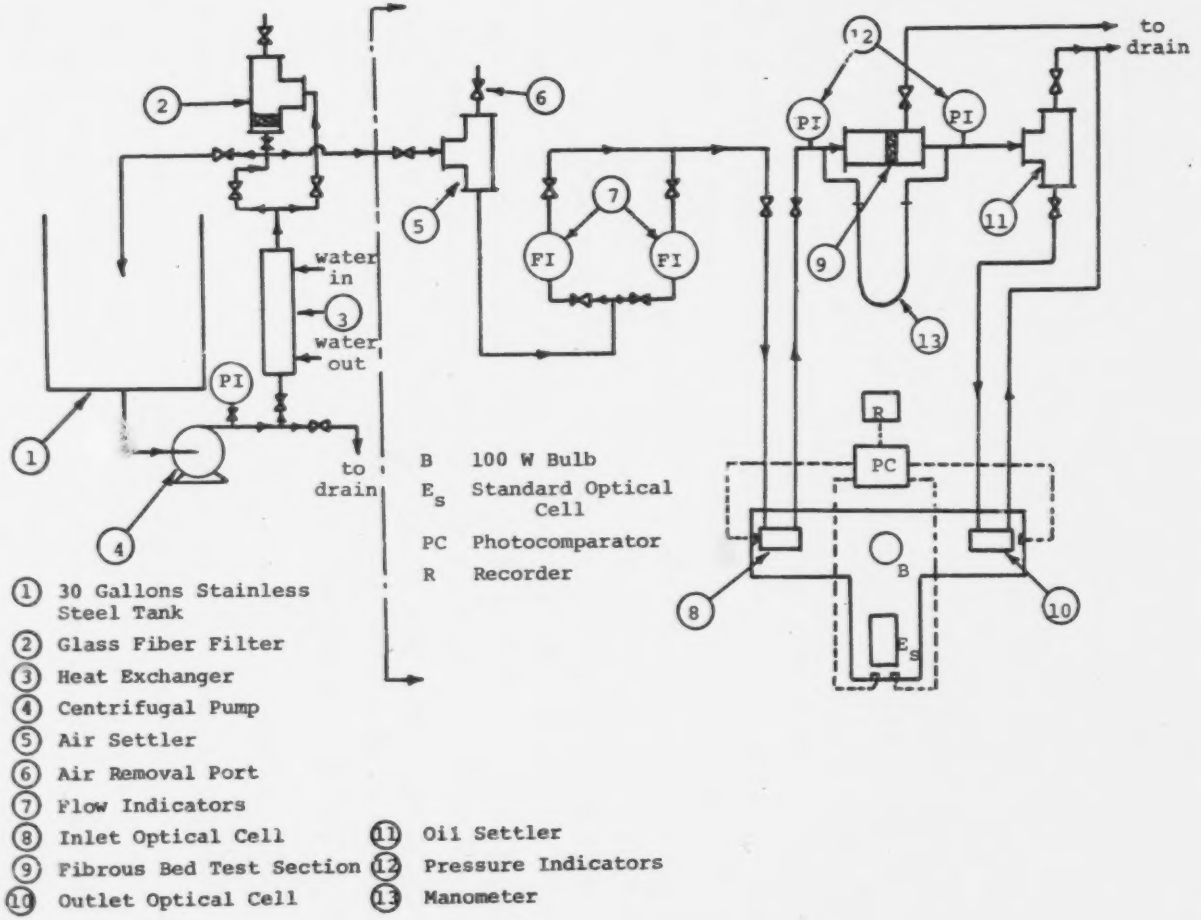


FIGURE 32 SCHEMATIC DIAGRAM OF ONCE-THROUGH SYSTEM

FIGURE 33. PHOTOGRAPH OF ONCE-THROUGH SYSTEM.

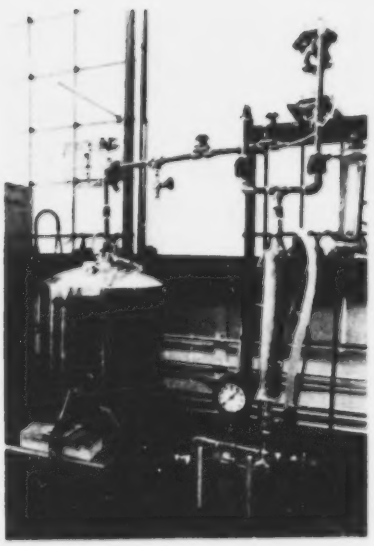


FIGURE 34. PHOTOGRAPH OF INLET SECTION ASSEMBLY OF ONCE-THROUGH SYSTEM.

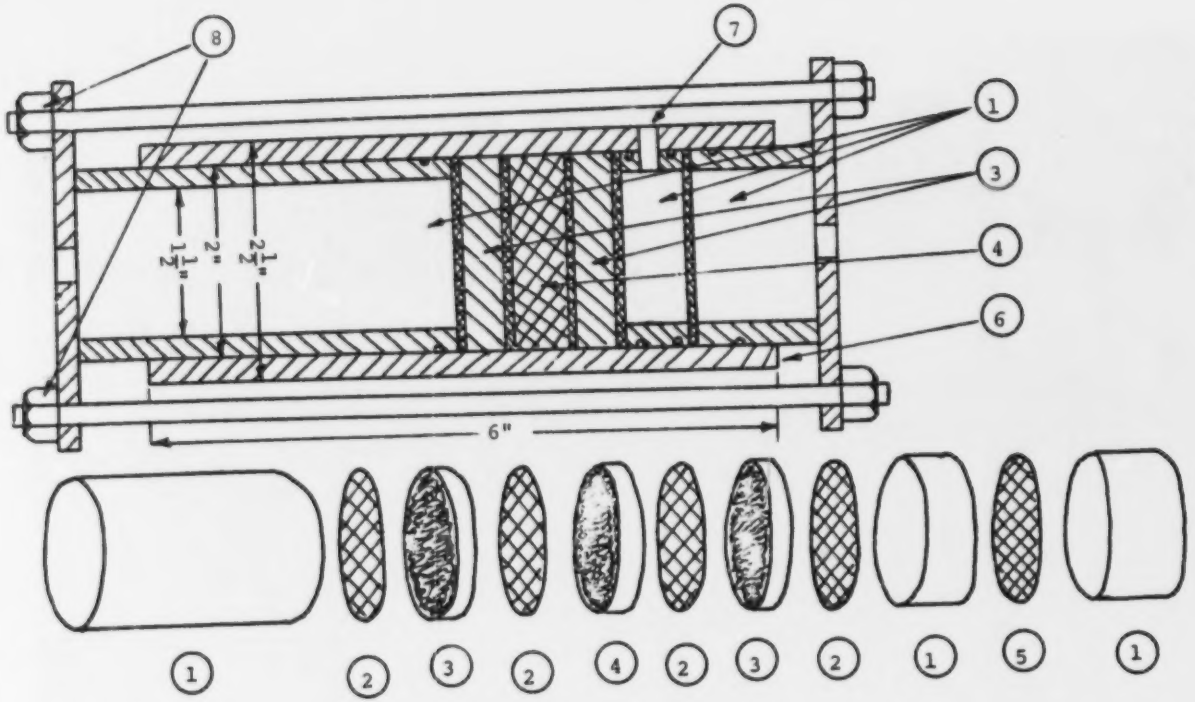
cell allowed visual observation of the bed operation. The coalesced drops of the dispersed phase were removed through an outlet (7) at the top of the cell. The desired compression of the bed was achieved by the adjustment of the tie bolts (8). The flow cross-section of the cell was 1.77 sq. inches.

The once-through system used a cell of similar construction but with a smaller flow cross section of 1 sq. in. This allowed the long period of operation of the bed, than one with 1.77 sq. in. cross-section for a given volume of emulsion in the feed tank.

The coalescer beds employed a 3.2μ fiber glass coated with bakelite (Owens Corning FM-004). In many cases front and rear layers of a 10.1μ bakelite coated fiber glass (Owens Corning - Aerocor) was also used.

Some runs were also made with uncoated 5.6μ fibers which were used as received and also with different hydrophobic coatings. The size distributions and physical properties of these fibers are given in Table 9 .

The fiber beds of 2 in. dia. were cut from fiberglas sheets by a 2 in. O.D. cutting die. The pads were weighed and placed in Plexiglas cell as shown in Figure 35. The first layer (3) is coarse coated fiberglas fibers of 10.1μ mean diameter, the second coalescer layer (4) is of fine coated fiberglas fibers of 3.2μ mean diameter, and third separator layer (3) is same as first layer. In some runs uncoated fibers of 5.6μ mean diameter were used as the coalescer layer. Some runs were made only with the single coalescer layer of various fibers used. The desired bed density and length of the bed was determined by draw up of the tie bolts.



1. Retainer Plexiglas Tubes
2. Wire Screens
3. 10.1μ Coarse Fiber Glass Layers
4. 3.2μ Fine Fiber Glass Layer
5. 100 mesh Monel Screen Coated with 0.005 in. of Teflon
6. External Plexiglas Tube
7. Coalesced Oil Outlet
8. Tie Bolts

FIGURE 35 SMALL SCALE COALESCER CELL WITH FIBROUS BED TEST SECTION

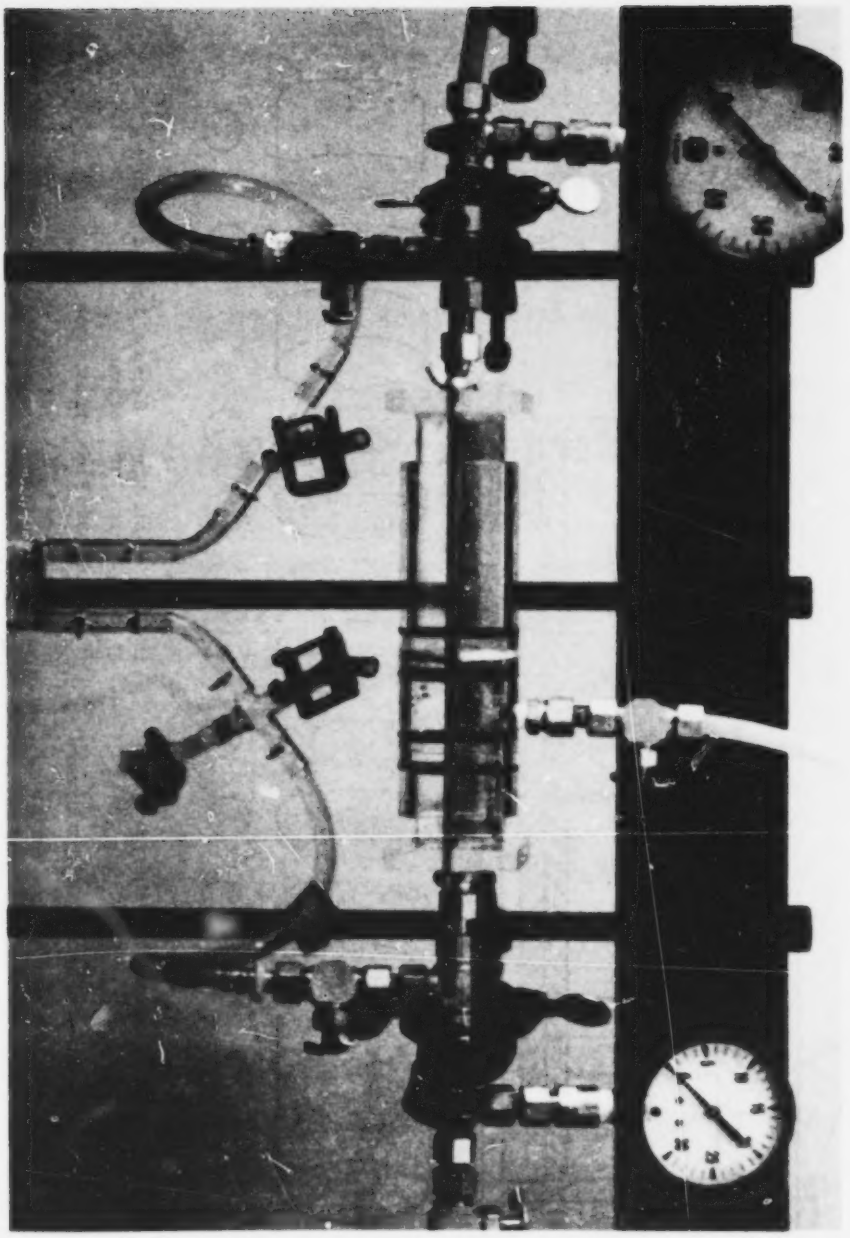


FIGURE 36. PHOTOGRAPH OF SMALL SCALE COALESCER CELL

TABLE 9

Physical Properties of the Fibers

Fine fiberglass (pink) Owens Corning FM-004

Size distribution

Interval Microns	No. of fibers	Weight/ft.^{2}	Density
1-2	11	0.025 lb./ft.^{2}	2.57$\pm$0.02 g./cm.^{3}
2-3	11		
3-4	18		
4-6	8		
6-8	2		
8-10	0		
	50		

Mean diameter = 3.2μ

Coarse fiberglass (yellow) Owens Corning "Aerocor"

Size distribution

Interval Microns	No. of fibers	Density
1-3	2	2.57$\pm$0.02 g./cm.^{3}
3-5	5	
5-7	4	
7-10	17	
10-15	18	
15-25	3	
>25	1	
	50	

Mean diameter = 10.1μ

Uncoated glass fibers

Size distribution

Internal Microns	No. of fibers	Density
1-3	10	2.50 g./cm.^{3}
3-5	24	
5-7	18	
7-9	8	
9-11	7	
11-13	3	
	70	

Mean diameter = 5.6μ

Oil Dispersions

Kerosene, 1/1 #30 single grade mobil oil/Kerosene and 1/1 ILS extracted oil/Kerosene were used as the dispersed phase. Some runs were also made with 0.1/1, 0.5/1 #30 oil/Kerosene. In all cases water was used as the continuous phase. Each run was made with fresh material. Before and after the apparatus was used, it was cleaned by flushing with water. Physical properties of the material used are given in Table 10.

Concentration Measurement by Light Transmission

The light transmission device used to determine the oil concentration is described by Sherony (16).

Measurement of Light Transmission

The diagram of the apparatus is shown in Figure 37. Light from a 100 watt bulb passes through an optical cell, which is filled with emulsion, and strikes the photocell. Light passing through another optical cell, filled with pure continuous phase, is also monitored by a photocell. The signals from both of these photocells are fed to a photocomparator. This photocomparator has been connected to a recorder. Details of the comparator circuit and instructions are given by Sherony (16).

Calibration

Both the outlet and inlet optical cells were calibrated for the Kerosene/water system. The same calibration was used for 1/1 #30 oil/Kerosene dispersed in water and 1/1 ILS oil/Kerosene dispersed in water.

An emulsion was prepared by adding known volume of dispersed phase to the continuous phase. The solubility of Kerosene in water at 75°F is approximately 20×10^{-6} volume per volume of continuous phase. This volume was subtracted from the total volume of dispersed phase added to give the

TABLE 10

Physical Properties of the Materials Used

Material	σ_{12} dynes/cm.	ρ_d gm./cm.^{3}	μ_d gm./cm.sec.	μ_c gm./cm.sec.	Temp. °F
Kerosene	37.8	0.816	0.0191	0.0092	75 ± 2
1/1 #30 oil/Kerosene	23.7	0.840	0.2320	0.0092	75 ± 2
1/1 ILS oil/Kerosene	17.5	0.860	0.3600	0.0092	75 ± 2

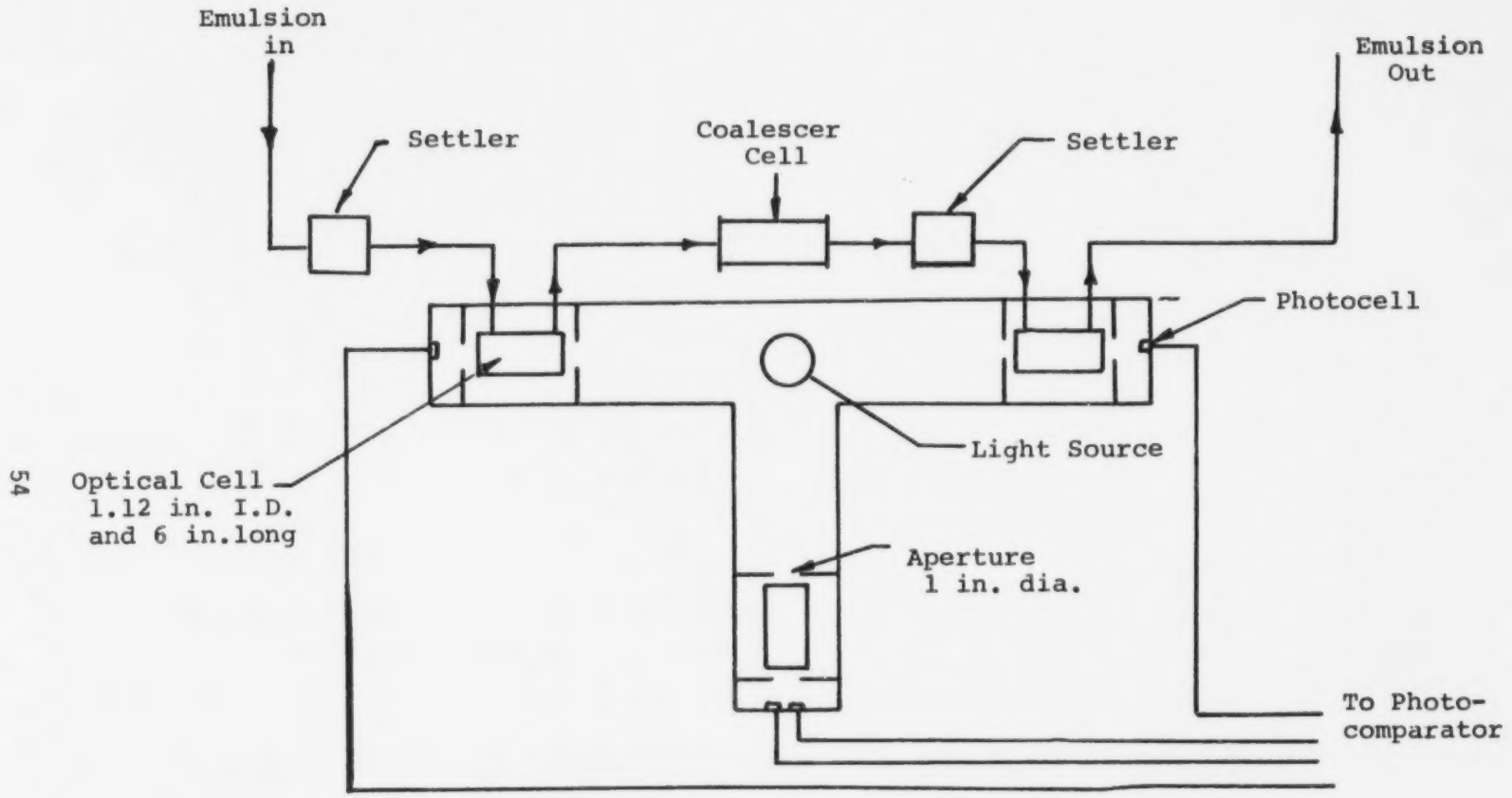


FIGURE 37 LIGHT TRANSMISSION APPARATUS

concentration of the dispersion. The emulsion was agitated and recycled for about an hour before samples were withdrawn from the tank and put into the two optical cells. The corresponding voltage readings were taken on the recorder connected with the photocomparator. Figure 38 and Table 11 show the calibration of light transmission apparatus for different concentration of dispersed phase. The photocomparator was balanced before and after calibration and during actual runs by filling the optical cells with pure continuous phase and setting the potentiometer.

Operating Procedure

The tank was filled with 6 liters of the continuous phase, and dispersed phase was added to bring the emulsion to the required concentration. The emulsion was agitated and recycled through the pump for about an hour. The temperature of the emulsion was maintained at 75° $\pm$ 2°F by circulating water through the cooling coil. The run was started at the maximum flow rate to drive out all the air from the bed and the system. The flow rate was then gradually decreased. In preliminary runs, the desired flow rate was maintained for about an hour, readings of pressure drop across the bed and inlet and outlet oil concentration were taken. Since the calibration given in Figure 38 is only good upto 230 ppm oil, higher concentrations were measured by diluting the sample with pure water.

In most runs, because of the time-dependent behavior of the pressure-drop, both pressure drop across the bed and inlet and outlet oil concentration data were taken as a function of time at various flow rates.

At the end of the run, the system was flushed with water and the next run was started with fresh materials.

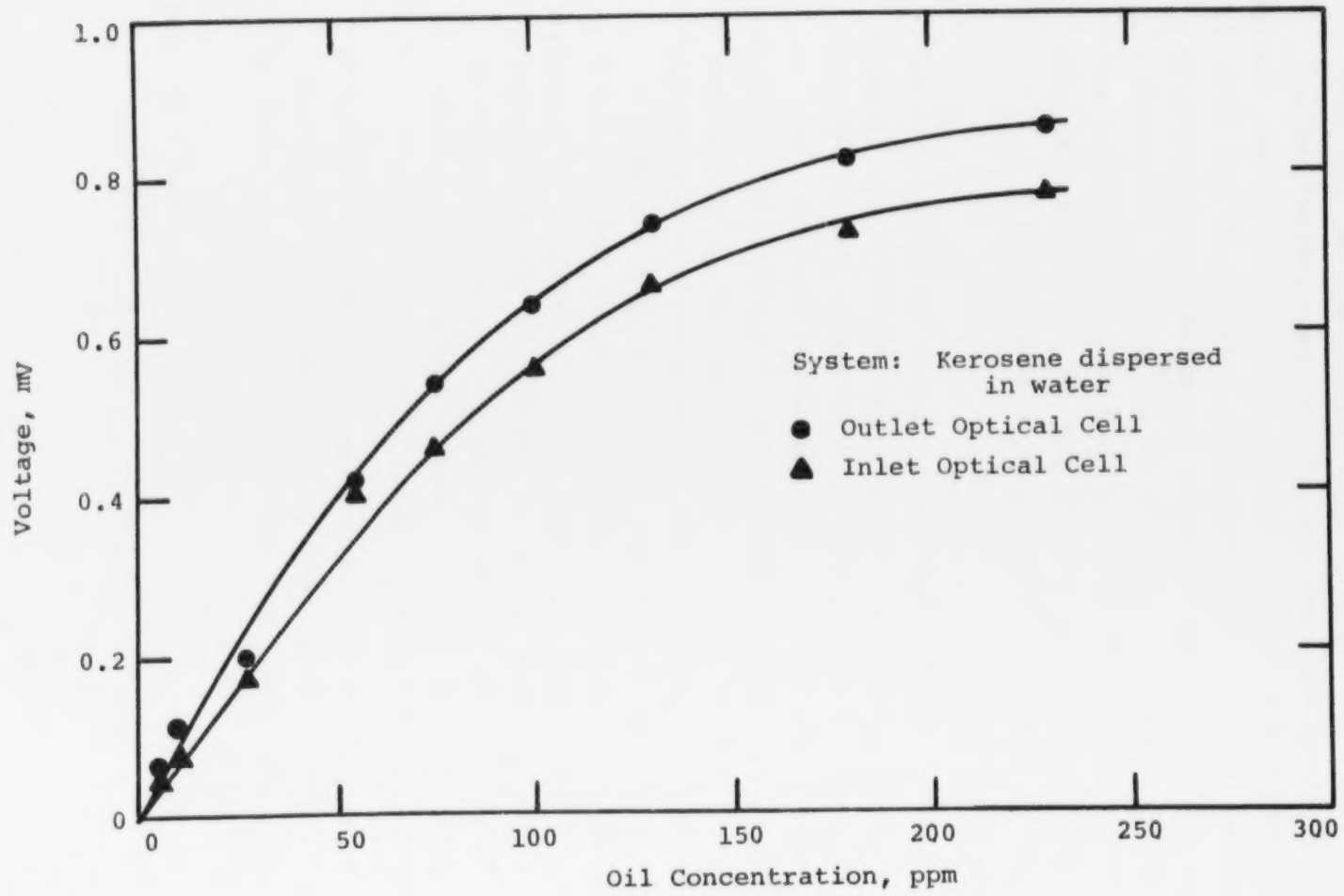


FIGURE 38 CALIBRATION OF LIGHT TRANSMISSION APPARATUS

TABLE 11

Calibration of Light Transmission Apparatus

System: Kerosene dispersed in water

Solubility: 20 ppm at 75° ± 2°F

concentration ppm	Inlet cell millivolts	Outlet cell millivolts
5	0.040	0.060
10	0.070	0.110
25	0.175	0.200
55	0.405	0.420
75	0.462	0.542
100	0.560	0.640
130	0.662	0.740
180	0.730	0.820
23(	0.778	0.860

SECTION VII

RESULTS OF SMALL COALESCER TESTS

Single Phase Flow Through Fibrous Beds

The pressure drop vs flow rate data were obtained for single phase flow using pure water flowing through single layer beds. The data for coated fibers (3.2μ mean diameter) and uncoated glass fibers (5.6μ mean diameter) are plotted in Figures 39 and 40 and are presented in Tables 12,13,14,15. For the same bed conditions, the pressure drop across the bed for the case of coated glass fibers is much higher than for uncoated glass fibers for same flow conditions. A slight time-dependent behavior of pressure drop was observed for coated fiberglass fibers.

The data were found to follow Darcy's Law. The pressure drop was proportional to flow rates except for 0.25 in. coated fiberglass bed at higher flow rates as shown in Fig. 40. The permeabilities $K_o\left(\frac{\mu_c v L}{\Delta p}\right)$ were computed from slopes of the curves given in Figures 39 and 40, and are given in the Tables 12,13,14,15. The permeability values for uncoated glass fibers are the same as reported by Spielman (17). However, the permeability values are much lower in the case of coated fiberglass fibers for the same conditions.

Two Phase Flow Through Fibrous Beds

The coalescence and pressure drop data of the preliminary investigation are shown in Table 16. The coalescence of Kerosene; 0.1/1, 0.5/1, and 1/1 #30 oil/Kerosene; and 1/1 ILS oil/Kerosene dispersed in water at superficial velocities from 0.15 to 1.96 ft./min. with inlet oil concentration of about 50 and 500 ppm. With coalescer layer of 5/16 or 5/64 in. length and about 11.6 lb./ft.^{3} density, oil in the effluent stream varied from 7 ppm to generally nondetectable oil for all systems at all velocities investigated. The coalescence of 1/1 ILS oil/Kerosene in water with 5/64 in.

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TABLE 12

Single Phase Flow Through Coated Fiberglass Fibers

Fiber Type: Coated fiberglass fibers
Mean Diameter: 3.2μ
Void fraction: 0.94
Bed density: 8.7 lb./ft.^{3}
Bed length: 0.13 in.

Velocity ft./min.	Δp psi	Reynolds number	Permeability $K_o (= \frac{\mu_c v L}{\Delta p})$ $(10^{-6} \times cm^2)$
0.4	0.38	0.018	0.024
0.73	0.68	0.012	
1.09	1.03	0.010	
1.44	1.38	0.009	
1.62	1.53	0.008	
1.80	1.70	0.006	
2.26	2.20	0.004	

TABLE 13

Single Phase Flow Through Coated Fiberglass Fibers

Fiber Type: Coated fiberglass fibers
Mean diameter: 3.2 μ
Void fraction: 0.90
Bed density: 15.8 lb./ft.^{3}
Bed length: 0.25 in.

Velocity ft./min.	Δp pai	Reynolds number	Permeability $K_o (= \frac{\mu_c v L}{\Delta p})$ $(10^{-6} \times cm^2)$
0.40	2.40	0.008	0.007
0.73	4.23	0.014	
1.09	6.11	0.020	
1.44	7.87	0.027	
1.62	8.24	0.031	
1.80	9.10	0.037	
2.26	10.59	0.043	

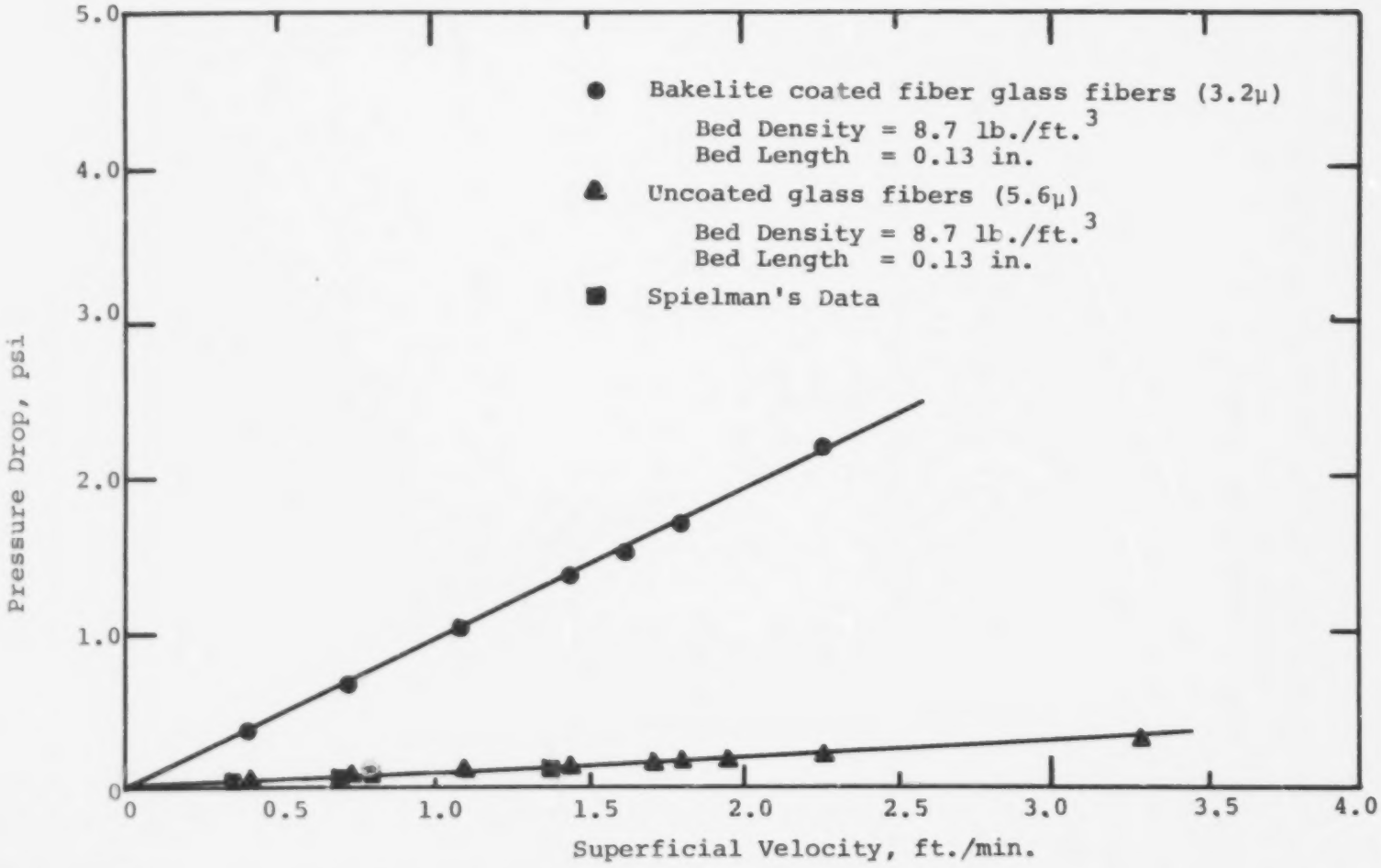


FIGURE 39 PRESSURE DROP VS SUPERVICIAL VELOCITY FOR SINGLE PHASE FLOW (VOID FRACTION 0.94)

TABLE 14

Single Phase Flow Through Uncoated Glass Fibers

Fiber Type: Uncoated glass fibers
Mean fiber diameter: 5.6μ
Void fraction: 0.94
Bed density: 8.8 lb./ft.^{3}
Bed length: 0.13 in.

Velocity ft./min.	Δp psi	Reynolds number	Permeability $K_o (= \frac{\mu_c v L}{\Delta p})$ $(10^{-6} \times cm^2)$
0.40	0.05	0.012	0.186
0.73	0.08	0.023	
1.09	0.12	0.034	
1.44	0.15	0.045	
1.70	0.16	0.053	
1.80	0.17	0.056	
1.95	0.18	0.061	
2.26	0.20	0.070	
3.29	0.32	0.102	

TABLE 15

Single Phase Flow Through Uncoated Glass Fibers

Fiber Type: Uncoated glass fibers
Mean fiber diameter: 5.6μ
Void fraction: 0.90
Bed density: 15.8 lb./ft.^{3}
Bed length: 0.25 in.

velocity ft./min.	Δp psi	Reynolds number	Permeability $K_o (= \frac{\mu_c v L}{\Delta p})$ $(10^{-6} \times cm^2)$
0.40	0.12	0.012	0.148
0.73	0.23	0.023	
1.09	0.33	0.034	
1.62	0.50	0.050	
2.26	0.71	0.070	
3.29	1.04	0.102	

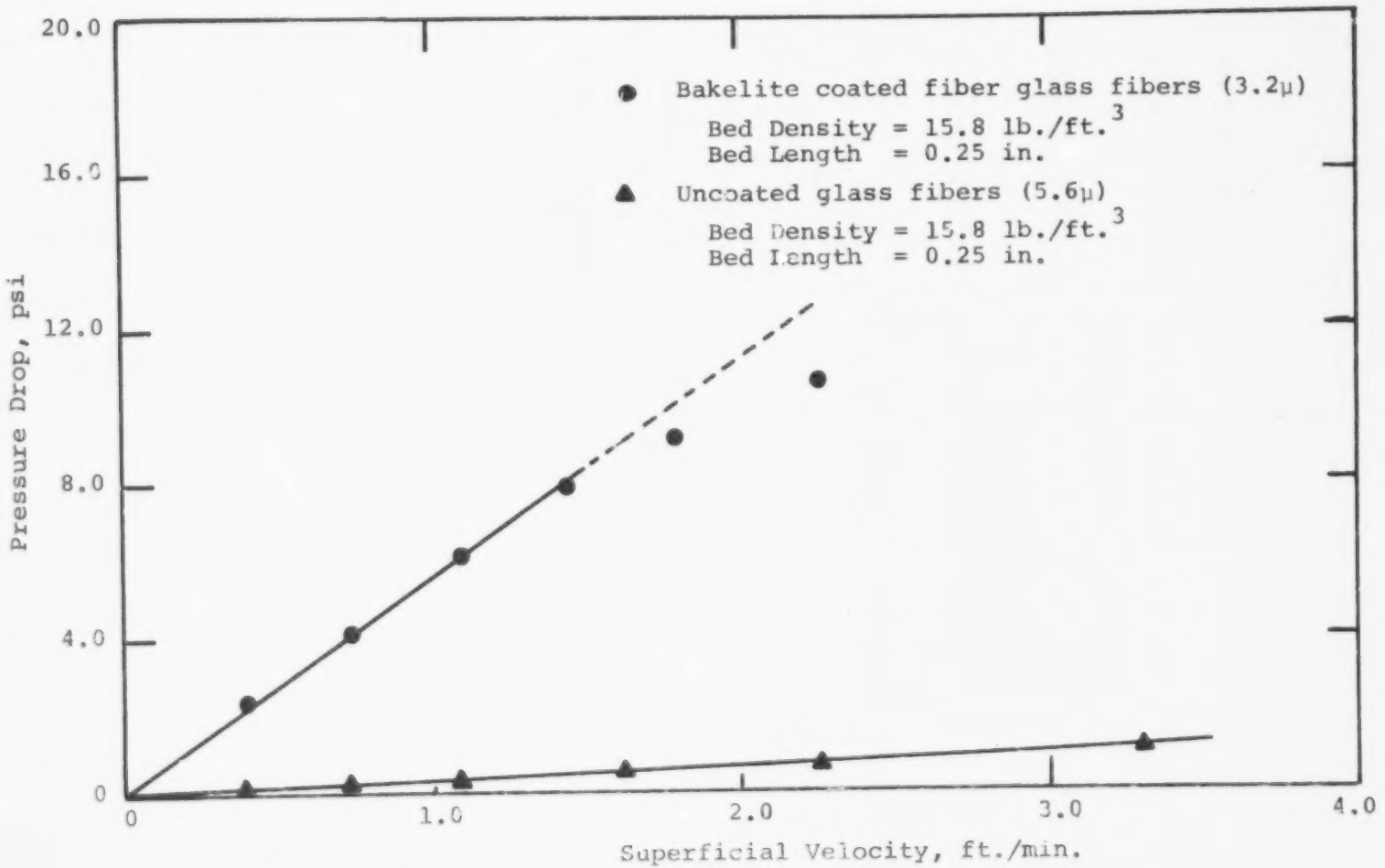


FIGURE 10 PRESSURE DROP VS SUPERFICIAL VELOCITY FOR SINGLE PHASE FLOW (VOID FRACTION 0.90)

TABLE 16

Preliminary Investigation of Coalescer Performance

Dispersed Phase	Bed density lb/ft^3	Bed length inches	Velocity ft/min	Pressure drop psi High Conc.	Pressure drop psi Low Conc.	Inlet Conc., ppm High	Inlet Conc., ppm Low	Outlet Conc., ppm High	Outlet Conc., ppm Low
Kerosene	* C.L. = 11.7	C.L. = 5/32	1.96	23.3	30.0	512	67	0	0
	** F.L. = 14.7	F.L. = 1/8	1.09	20.4	28.2	512	67	0	0
	*** S.L. = 11.8	S.L. = 5/32	0.48	11.0	15.8	512	67	0	0
		**** T.L. = 7/16	0.15	9.2	6.0	512	67	0	7
Kerosene	C.L. = 11.6	C. L. = 5/64	1.96	21.5	30.0	450	53	30	0
	F.L. = 14.7	F.L. = 1/16	1.09	15.8	20.8	450	53	17	1
	S.L. = 11.6	S.L. = 5/64	0.48	8.1	11.2	450	53	6	0
	Pre-soaked with dispersed phase	T.L. = 7/32	0.15	3.9	5.2	450	53	17	3
0.1/1 #30 oil/kero.	C.L. = 11.6	C.L. = 5/64	1.96	18.0	30.0	510	48	0	2
	F.L. = 14.4	F.L. = 1/16	1.09	12.2	20.7	510	48	0	2
	S.L. = 11.8	S.L. = 5/64	0.48	7.0	11.2	510	48	0	1
		T.L. = 7/32	0.15	4.8	5.0	510	48	0	0
0.5/1 #30 oil/kero.	C.L. = 11.6	C.L. = 5/64	1.96	15.3	24.8	495	60	3	1
	F.L. = 14.5	F.L. = 1/16	1.09	10.0	15.2	495	60	1	0
	S.L. = 11.5	S.L. = 5/64	0.48	5.2	8.0	495	60	0	0
		T.L. = 7/32	0.15	2.5	3.2	495	60	1	0
1/1 #30 oil/kero.	C.L. = 11.7	C.L. = 5/64	1.96	16.0	23.3	460	68	1	1
	F.L. = 14.4	F.L. = 1/16	1.09	10.8	14.0	460	68	2	0
	S.L. = 11.8	S.L. = 5/64	0.48	5.8	6.9	460	68	1	0
		T.L. = 7/32	0.15	3.0	2.9	460	68	3	0
1/1 ILS oil/kero.	C.L. = 11.8	C.L. = 5/64	1.96	17.8	24.8	570	65	5	0
	F.L. = 14.5	F.L. = 1/16	1.09	14.6	16.0	570	65	6	0
	S.L. = 11.7	S.L. = 5/64	0.48	9.8	8.2	570	65	3	0
		T.L. = 7/32	0.15	5.0	3.8	570	65	4	1

Table 16 continued

1/1 ILS oil/kero.	C.L. = 5.9 F. L. = 7.3 S.L. = 5.9	C.L. = 5/64 F.L. = 1/16 S.L. = 5/64 T.L. = 7/32	1.96 1.09 0.48 0.15	7.0 5.2 3.5 2.0	- - - -	480 480 480 480	- - - -	70 91 130 -	- - - -
1/1 ILS oil/kero.	C.L. = 8.7 F.L. = 11.8 S.L. = 8.2	C.L. = 5/64 F.L. = 1/16 S.L. = 5/64 T.L. = 7/32	1.96 1.09 0.48 0.15	6.9 5.5 3.8 -	- - - -	470 470 470 470	- - - -	62 35 22 -	- - - -

* Coalescer layer
** Filter layer
*** Separator layer
**** Total length

thick and 5.9 lb./ft.^{3} and 8.7 lb./ft.^{3} densities of coalescer layer was found to be poor.

The pressure drop across the bed was found to be time dependent. The data shown in Table 16 are taken at the end of about 30 minutes.

The time-dependent behavior of pressure drop for Kerosene dispersed in water with inlet oil concentration of about 100 ppm for four different velocities is shown in Figure 41. The pressure drop continuously increases with time and does not appear to reach steady state value. To check this, a test was made under the similar conditions for a long period of time. The data for the test are plotted in Figure 42. In 810 minutes the pressure drop across the bed reached a value of 44 psi at 1.95 ft./min. which was approximately the maximum discharge pressure of the pump. The time-dependent behavior for 1/1 ILS oil/Kerosene dispersed in water is shown in Figure 43. The coalescence efficiency was essentially 100%.

The rise in pressure drop across the bed with time is due to increase in holdup of the dispersed phase. Regeneration of the bed using water and methanol to remove the accumulated oil was attempted. The pressure drop and coalescence performance data for Kerosene dispersed in water are given in Table 17. The methanol regeneration gave almost the similar pressure time characteristics as the fresh bed but the coalescence performance was poorer than fresh bed. Beds could not be regenerated by water.

Most of the data reported in the literature have been taken using uncoated glass fibers. Tests were made to evaluate both uncoated and coated glass fibers, the latter coatings being commercially available silicone materials that produce hydrophobic surfaces. The pressure drop and coalescence performance data for Kerosene dispersed in water are given in Table 18.

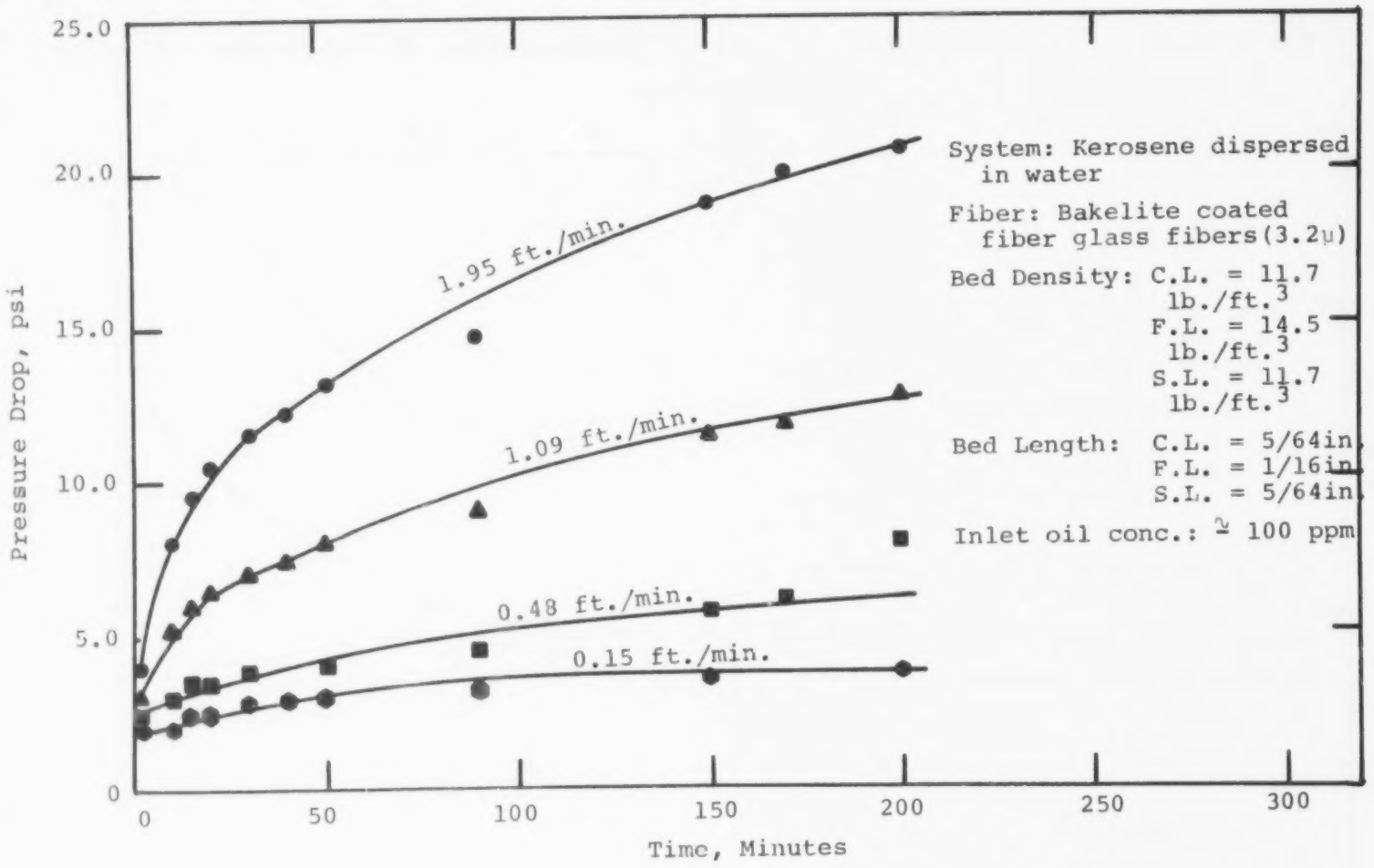


FIGURE 41 TIME-DEPENDENT BEHAVIOR OF PRESSURE DROP AT DIFFERENT SUPERFICIAL VELOCITIES FOR BAKELITE COATED FIBER GLASS FIBERS

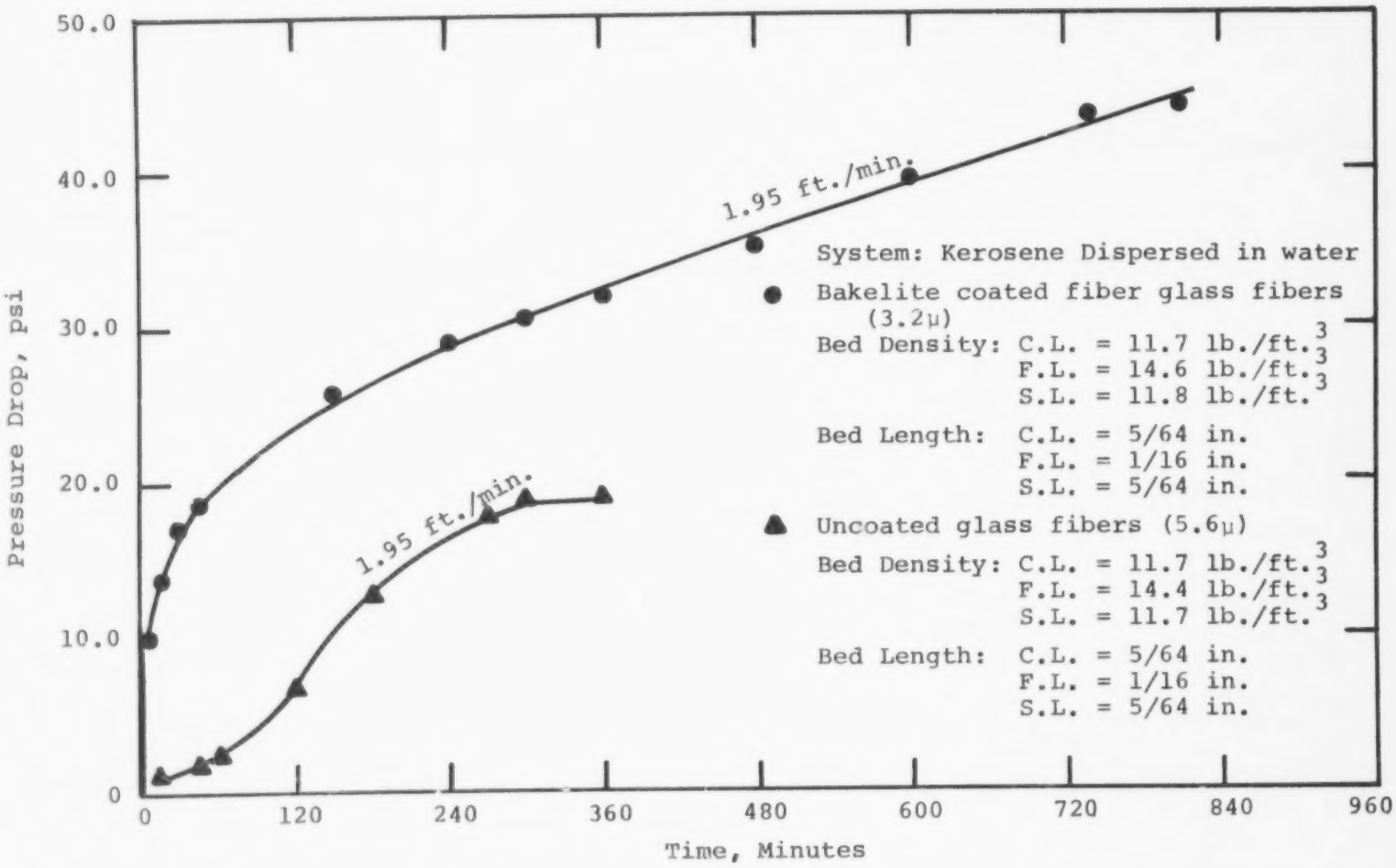


FIGURE 42 COMPARISON OF TIME-DEPENDENT BEHAVIOR OF PRESSURE DROP FOR COATED FIBER GLASS AND UNCOATED GLASS FIBERS

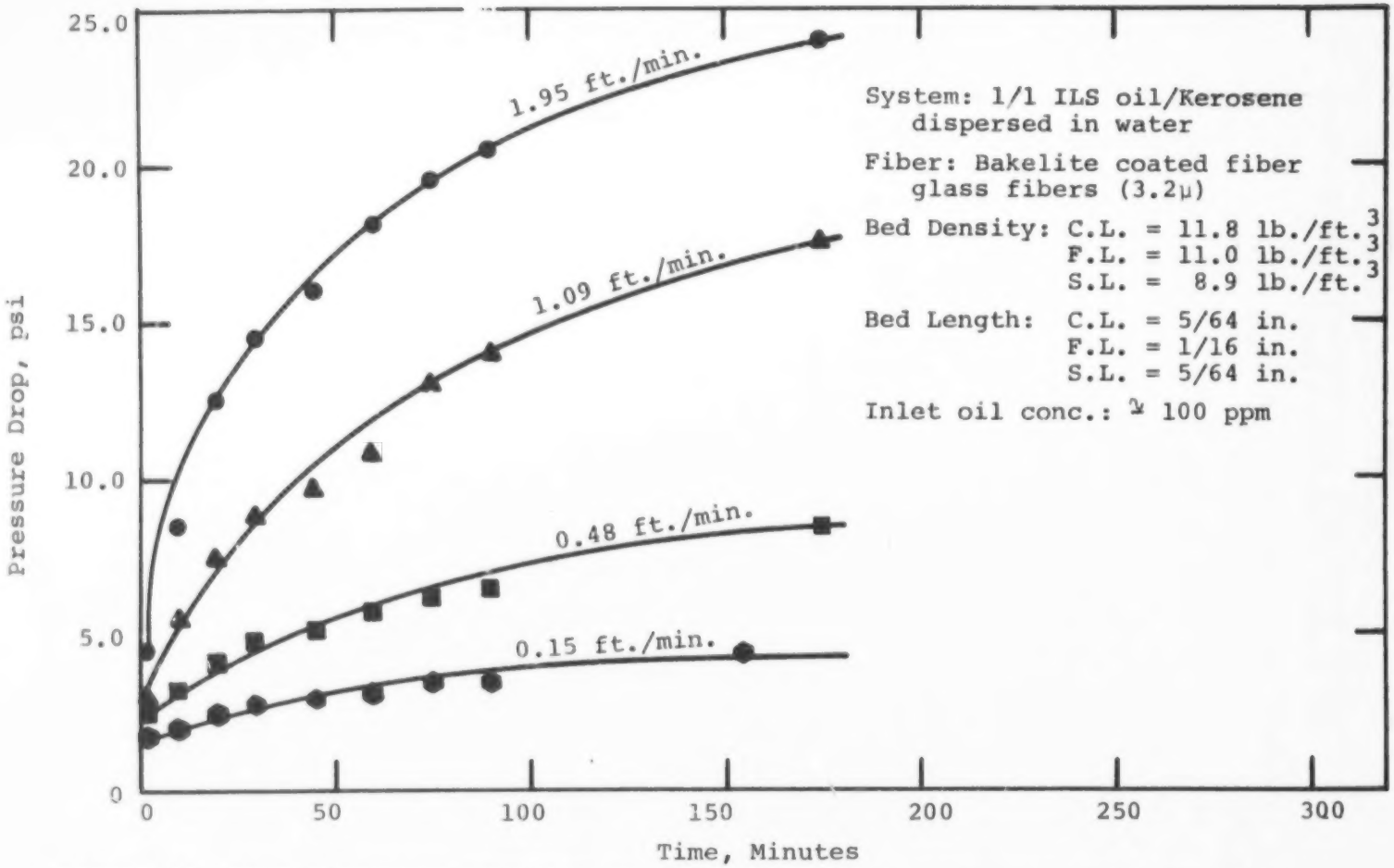


FIGURE 43 TIME-DEPENDENT BEHAVIOR OF PRESSURE DROP AT DIFFERENT VELOCITIES FOR 1/1 ILS OIL/KEROSENE DISPERSED IN WATER

TABLE 17

Coalescer Performance With and Without Regeneration for Coated Fiberglass Fibers

System: Kerosene dispersed in water

Bed density: *C.L. = 11.6 lb./ft.^{3}

**F.L. = 11.5 lb./ft.^{3}

***S.L. = 9.2 lb./ft.^{3}

Bed length: C.L. = 5/64 in.

F.L. = 1/16 in.

S.L. = 5/64 in.

Fresh Bed

Time min.	Velocity ft./min.	Δp psi	Inlet oil conc., ppm	Outlet oil conc., ppm
0	1.95	3.8	-	-
20	1.95	15.5	120	0
21	0.48	5.0	-	-
40	0.48	10.5	58	1
41	1.09	15.0	-	-
70	1.09	17.0	50	1
71	0.15	2.0	-	-
100	0.15	3.0	53	1
Regeneration with water at 1.09 ft./min. for about an hour				
0	1.95	20.5	-	-
30	1.95	25.0	250	40
31	1.09	12.8	-	-
60	1.09	16.5	135	25
Regeneration with methanol				
0	1.95	3.0	-	-
10	1.95	12.0	168	8
20	1.95	15.4	100	13
21	1.09	9.0	-	-
35	1.09	12.0	70	9

* C.L. = Coalescer Layer

** F.L. = Filter Layer

*** S.L. = Separator Layer

TABLE 18

Coalescer Performance with Uncoated Glass Fibers
and Uncoated Glass Fibers Treated with Various Hydrophobic Coatings

Fiber	Time for each run min.	Velocity ft./min.	Pressure drop psi	Inlet oil conc. ppm	Outlet oil conc. ppm
(a) Bakelite coated, Single coalescer layer cell 7/32 in. thick & 12.2 lb./ft.^{3} bed density	5	4.41	42.0	215	2
	5	3.29	43.0	150	1
	10	2.26	40.0	117	1
	10	1.62	35.0	69	1
	10	1.09	22.5	40	0
(b) Uncoated glass, single coalescer layer cell, 7/32 in. thick and 12.4 lb./ft.^{3} bed density	30	4.41	6.2	160	8
	30	3.29	4.9	290	8
	30	2.26	4.0	175	10
	30	1.62	3.4	260	7
	30	1.09	3.2	160	8
(c) Uncoated glass, three layer cell with inside coalescer layer 5/64 in. thick and 11.8 lb./ft.^{3} bed density	30	4.41	5.8	25	12
	30	3.29	4.5	140	17
	30	2.26	3.4	65	12
	30	1.95	3.4	81	15
	30	1.09	2.2	49	9
(d) Uncoated glass coated with L-45 "Silicone" (Union Carbide) in benzene, three layer cell as in (c) with 11.7 lb./ft.^{3} bed density	30	4.41	7.0	72	17
	75	2.26	9.5	55	12
	30	1.62	10.0	96	14
	30	1.09	9.5	137	15
(e) Uncoated glass coated with 1% Z-6040 "Silane" (Dow Corning) in water three layer cell as in (c) with 11.7 lb./ft.^{3} bed density	30	4.41	6.5	82	15
	45	2.26	8.8	44	11
	30	1.62	10.2	62	13
	30	1.09	10.8	102	12

(Continued)

TABLE 18 (Continued)

	Time for each run min.	Velocity ft./min.	Pressure drop psi	Inlet oil conc. ppm	Outlet oil conc. ppm
(f) Uncoated glass coated with 0.3% Z-6020 "Silane" (Union Carbide) in water, three layer cell as in (c) with 11.7 lb./ft.^{3} bed density	30	4.41	11.2	93	40
	40	2.26	14.0	65	21
	50	1.62	14.2	59	40
	30	1.09	12.5	117	60
(g) Uncoated glass, coated with 1% A-172 "Vinyl Silane" (Union Carbide) in water, three layer cell as in (c) with 11.8 lb./ft.^{3} bed density	30	4.41	4.5	44	13
	30	2.26	11.0	160	13
	40	1.62	12.5	87	12
	30	1.09	11.8	220	12
(h) Uncoated glass, coated with DC-200 in toluol, three layer cell as in (c) with 11.7 lb./ft.^{3} bed density.	30	1.62	9.2	59	18
	30	1.09	14.5	140	12

The data show that practical pressure drops are obtained with uncoated glass and similarly with uncoated glass treated with different hydrophobic coatings. In all cases, the coalescence performance is poorer than the commercially available bakelite coated fiberglass even when using much thicker coalescer layer.

The time-dependent behavior of the pressure drop was also observed in case of uncoated glass fibers. The Table 19 gives time vs pressure drop data for bakelite coated and uncoated glass fibers. These are plotted in Figure 42.

The pressure drop data on the uncoated glass fibers indicates that there was initial slow rate of increase followed by rapid rate of increase. The final hour indicated no increase in pressure drop. The coalescer performance appears to be increasing with increase in pressure drop. However, the performance is still much poorer than bakelite coated fiberglass which gives the same optimum performance of 1 to 2 ppm at both low and high pressure drops. The rate of increase of pressure drop in case of bakelite coated fiberglass is higher than uncoated glass fibers.

Good coalescence data requires a system free of solid particles. The accumulation of these solid particles in the bed changes the surface characteristics and hence the pressure drop behavior and coalescence performance. Microscopic examination of bed at the end of a run revealed the presence of black particles probably from the rubber impeller of the pump. Consequently, a new 3/4 HP centrifugal pump was used to eliminate the possibility of any particles from rubbing surfaces.

The data reported here and those reported in the literature indicate that the lower pressure drops are obtained with uncoated glass fibers. The oil removal efficiency [1 - outlet oil conc./inlet oil conc.] is however much lower. Tests

TABLE 19

Time Versus Pressure Drop for Coated Fiberglass Fibers and Uncoated Glass Fibers

Fiber	Time min.	velocity ft./min.	Pressure drop psi	Inlet oil conc. ppm	Outlet oil conc. ppm
(a) Bakelite coated fiber glass, three layer cell with inside coalescer layer 5/64 in. thick and 11.7 lb./ft.^{3} bed density	6	1.95	10.0	-	-
	15		13.8	96	1
	30		17.0	-	-
	45		18.8	63	2
	180		25.8	84	2
	240		29.2	-	-
	300		30.7	-	-
	360		32.0	62	2
	480		35.4	-	-
	600		39.5	-	-
	750		43.5	-	-
	810		44.0	-	-
(b) Uncoated glass, three layer cell with inside coalescer layer 5/64 in. thick and 11.7 lb./ft.^{3} bed density	15	1.95	1.2	117	48
	45		1.8	50	27
	60		2.4	89	25
	120		6.8	65	20
	180		12.8	50	12
	270		17.8	77	12
	300		19.0	50	12
	360		19.0	-	-

made with uncoated 8μ glass fibers of uniform size (which was used by Sherony (16)) gave steady state pressure drop shown in Figure 44, however oil removal efficiency was only 10 to 15%. The bakelite coated fiber glass, which exhibit higher and time dependent pressure drops, give oil removal efficiencies between 90 and 99%. The data taken in this study and given in Table 20 permits the following observation. The oil removal efficiency for bakelite coated fibers is more than 90%. The lower efficiency values given in Table 20 are due to the rapid change in inlet oil concentration (outlet oil concentration is almost constant) with time. The change in inlet oil concentration is due to the oil holdup which occurs in a recirculating system. Consequently a once-through system was set up. The data for Kerosene dispersed in water with once through system is given in Table 21. The data reveal that the inlet oil concentration is almost constant and oil removal efficiency is above 90%. The slight increase in outlet oil concentration with time is due to air bubbles passing through the light transmission apparatus. The pressure drop vs. time plot for both recirculating and once-through system shown in Figure 44 indicates similar time-dependent behavior of pressure across coated fiber glass beds.

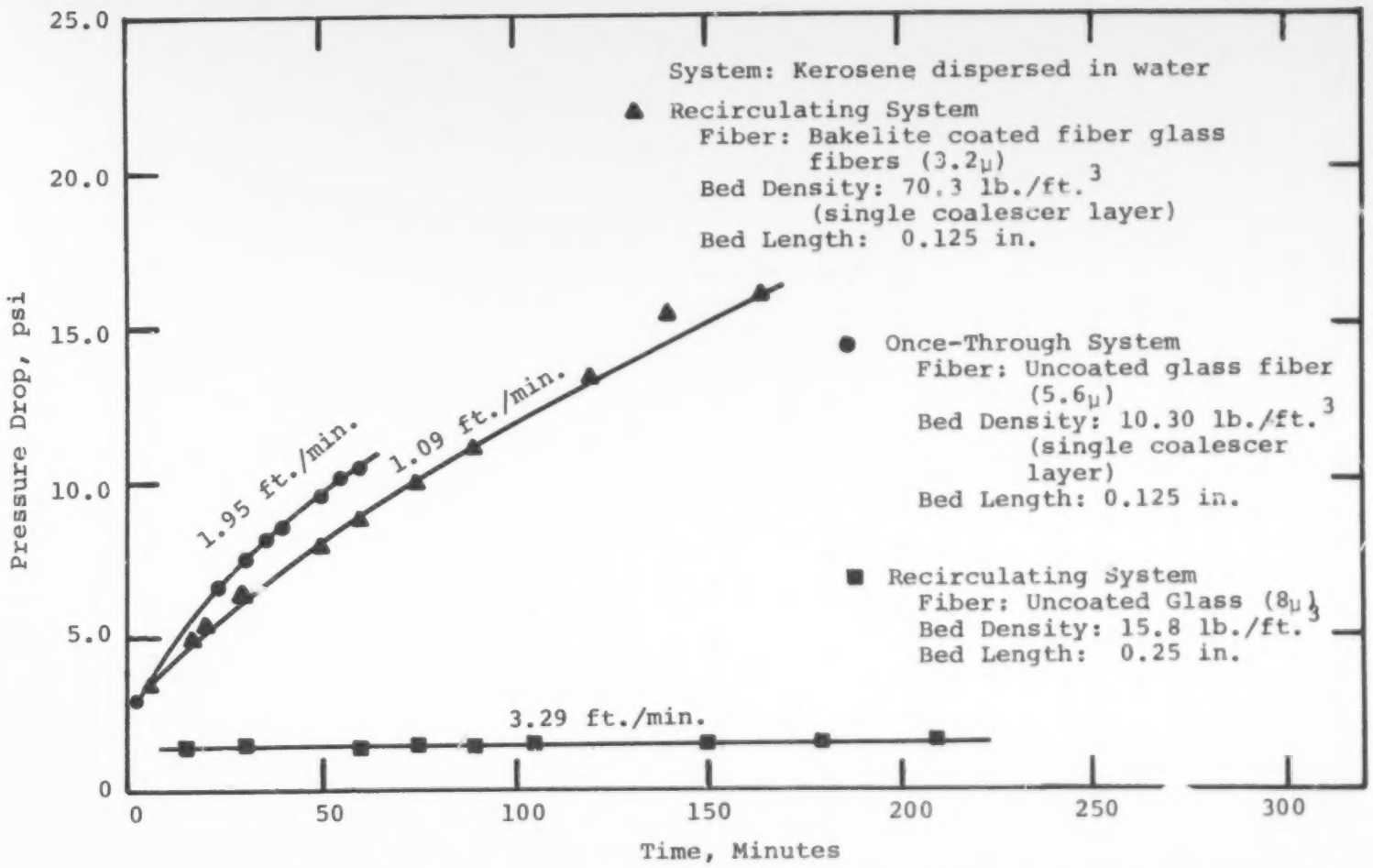


FIGURE 44 COMPARISON OF TIME-DEPENDENT BEHAVIOR OF PRESSURE DROP FOR ONCE-THROUGH AND RECIRCULATING SYSTEMS

TABLE 20

Coalescer Performance Data for Recirculating System

System: Kerosene dispersed in water
Fiber: coated fiber glass
Bed density: 10.3 lb./ft.^{3}
Bed length: 0.125 in.

Time min.	Velocity ft./min.	Δp psi	Inlet oil conc. ppm	Outlet oil conc. ppm	oil removal efficiency
0	1.95	3.0	-	-	-
23		6.6	57	6	0.89
30		7.6	31	4	0.87
35		8.2	20	4	0.76
40		8.6	11	4	0.65
*		-	-	-	-
50		9.5	93	6	0.93
55		10.2	76	7	0.90
60		10.4	52	7	0.86
62	1.09	6.4	-	-	-
65		-	48	5	0.89
70		8.0	40	5	0.88
85		8.9	17	3	0.82
90		9.3	10	3	0.70

* Flow of emulsion was stopped through the cell, 2 ml. of Kerosene was added and emulsified for about 1 hr. It was then passed through the coalescer cell.

TABLE 21

Coalescer Performance Data for Once-Through System

System: Kerosene dispersed in water
Fiber: coated fiber glass
Bed density: 10.3 lb./ft.^{3}
Bed length: 0.125 in.

Time min.	Velocity ft./min.	Δp psi	Inlet oil conc. ppm	Outlet oil conc. ppm	oil removal efficiency
5	1.09	3.48	-	-	-
10		-	175	1	0.99
16		4.93	-	-	-
20		5.35	175	0	1.00
30		6.34	175	8	0.96
50		7.91	175	8	0.96
60		8.82	172	9	0.95
75		9.99	170	9	0.95
90		11.15	168	10	0.94
120		13.43	165	11	0.93
150		15.39	162	12	0.93
165		16.06	160	14	0.91

SECTION VIII

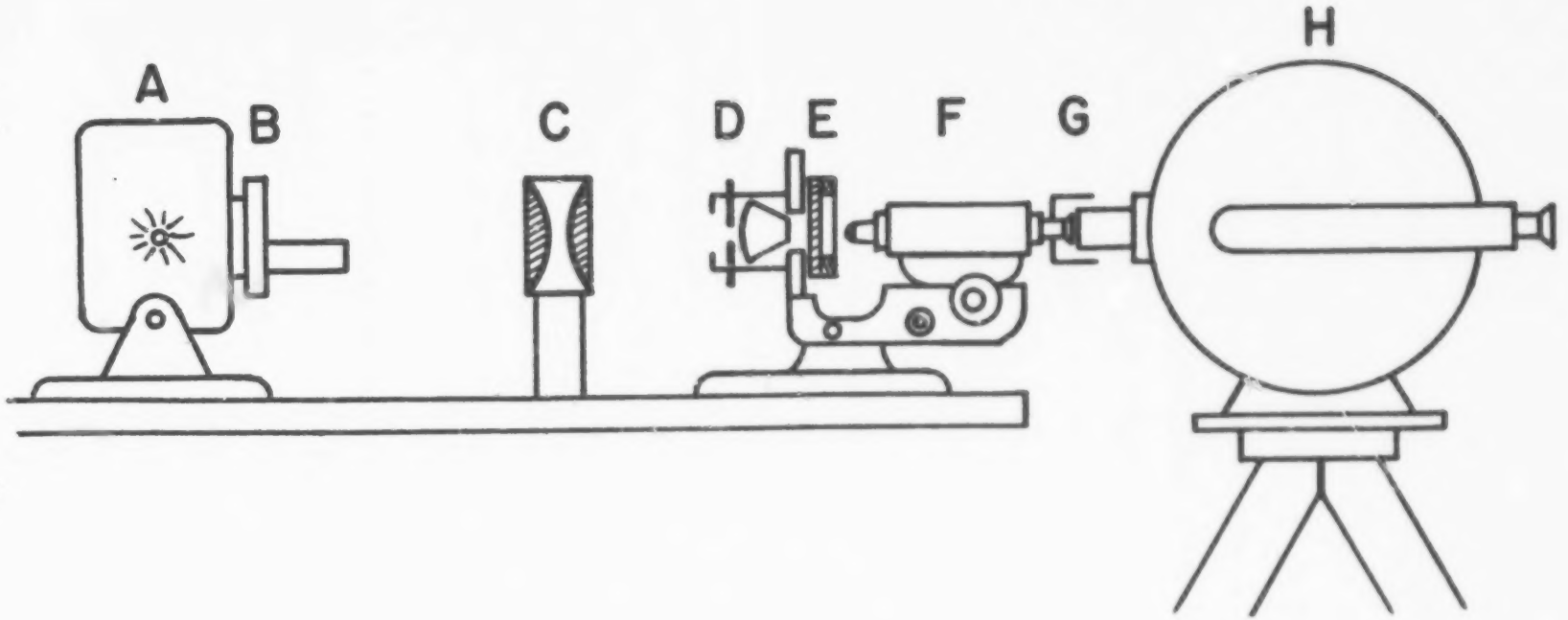
MICROSCOPIC STUDY OF FIBROUS BED COALESCER

The qualitative analysis of coalescence phenomena in a fibrous bed was carried out by observing the bed in operation. The observations were made under a microscope and recorded by high speed motion picture photography.

The optical system for taking pictures through microscope is shown in Figure 45, and has been described by Kintner et al. (18). The approach of the oil drops (average size 10μ) to the fiber and the coalescence of the drops are shown in Figure 46.

It was observed that coalescence occured in two ways. The most common type of coalescence was that between a drop in the main stream and a drop attached to a fiber when collision occured. The second type of coalescence resulted when two drops were in contact on a fiber. In all systems investigated it was possible to find drops attached to fibers. Systems which showed a high population density of drops attached to fibers, coalescence frequency with attached drops was high.

From the above observations it is believed that the primary mechanism of coalescence in fibrous beds involves attached drops, and that the three phase systems in which there are relatively few drops of secondary emulsion attached to the fibers will be systems with poor coalescing effectiveness.



A. Bausch & Lomb illuminator, 6-volt, 18-ampere lamp
B. Rack for heat absorber and light filters
C. Condensing lens system
D. Substage condenser and iris diaphragm
E. Flow cell containing fibers
F. Microscope optical system
G. Light trap
H. Fastax WF3 camera

FIGURE 45 APPARATUS FOR HIGH SPEED CINEPHOTOMICROGRAPHY

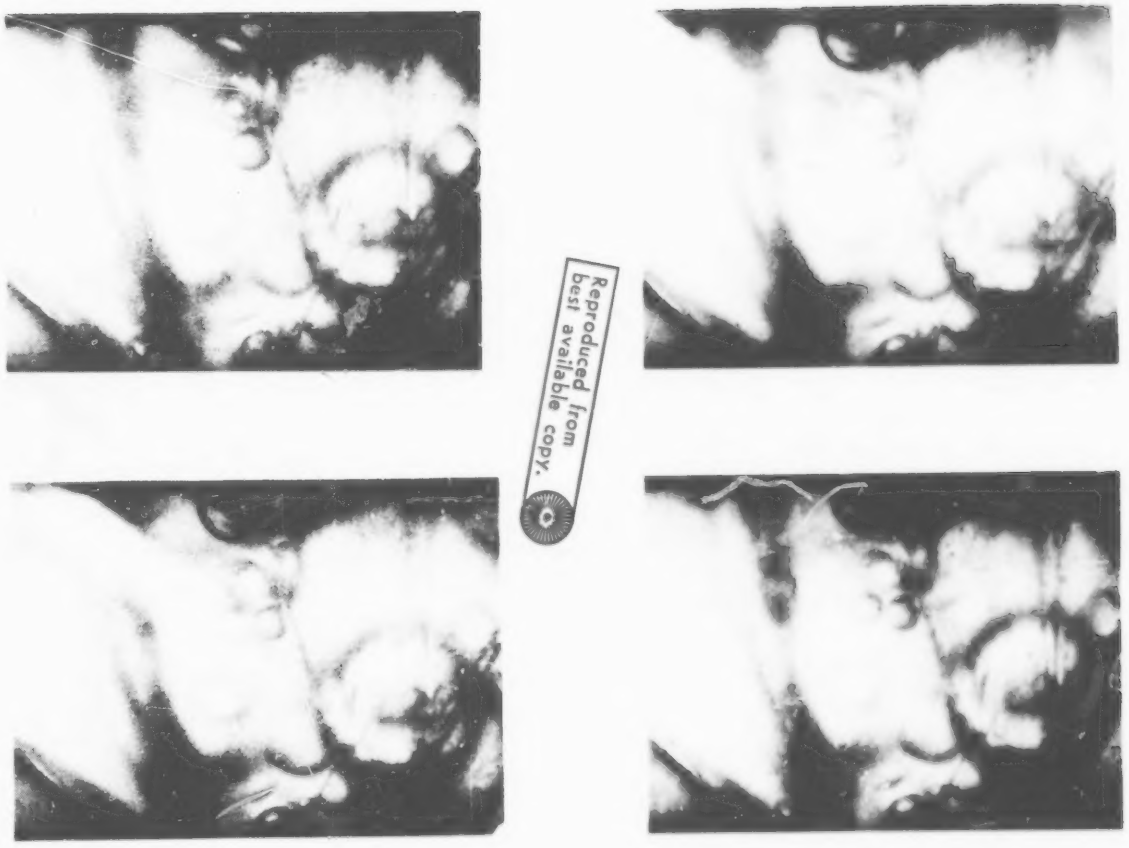


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FIGURE 46. MICROSCOPIC PICTURES OF OIL DROPS COALESCING IN A FIBROUS BED.

SECTION IX

STABILIZATION TESTS

Preliminary tests on stabilizing the 3.2μ coalescing fibers were made by treating them with 10% isobutyl methacrylate resin dissolved in methylene chloride. This material was used because of availability. Information and samples of phenol formaldehyde resins which could be used have not been obtained as yet after two months of effort.

The following technique of applying the resin should be directly applicable to forming the diaphragm in situ in the large cell. The 3.2μ glass, after being saturated with the solution of 10% resin in methylene chloride, is compressed between 2 layers of 1 in. 10.1μ glass on each side to 1/4 in. The two end layers of 10.1μ glass were then replaced with fresh 10.1μ glass, compressed to 1/4 in., clamped, and dried at 100°C for 1 hour. The final assembly of 2/1/2 in. of uncompressed 10.1μ/3.2μ/10.1μ glass corresponds to the diaphragm assembly used in Runs 2 thru 7.

The diaphragms were evaluated in the test unit shown in Fig. 47. The fiber bed (7) is maintained at 1/4 in. spacing by means of spacer cylinders (1), between perforated disk (5). The disk is provided with 1/2 in. opening in the holder (4). The spacer bars (1) are bolted (2) between the saddles (3) which are threaded to (4). The periphereal seals are provided by the O-ring (6) placed in very shallow grooves. This construction insures that any leakage thru the entrant layers of 10.1μ glass can not bypass to the exit side and contaminate the effluent. The flow area is only nominally 1/2 in.

Stabilization Tests-Results

The results of the tests on the stabilized fibers are shown in Table 22. The same performance and pressure drop as in the large cell are obtained. Treatment of the diaphragm with hexane after 20 hours resulted in a regenerated

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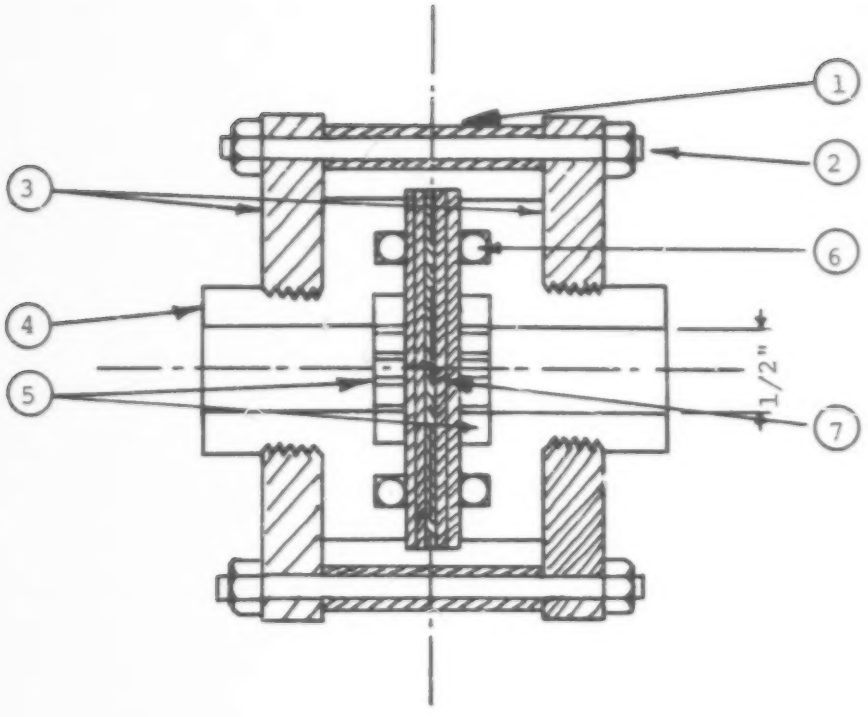

① Spacer Cylinder
② Tie Bolt
③ Saddle Clamp
④ Inlet Port
⑤ Perforated Disks
⑥ O-Rings
⑦ Fiberous Bed Test Section

FIGURE 47 ASSEMBLY FOR STABILIZATION TESTS

TABLE 22

Regeneration Tests on Stabilized Fibers

Time hours	Velocity fpm	Flow Rate GPM/ft²	Temp. °F	Pressure Drop psi	Oil T U*	
					Influent	Effluent
0	3.1	22.50	-	1.93	24.0	3.00
.45	6.2	46.40	-	1.93	-	1.50
.53	.3	2.24	-	0.97	-	.85
.53	.8	5.98	-	1.93	-	.75
.62	1.2	8.98	96	2.90	10.0	.75
.78	.7	5.24	92	-	-	-
.98	.7	5.24	90	3.62	-	.95
1.02	.9	6.74	90	4.39	-	-
1.06	1.1	8.23	86	5.93	-	1.10
1.20	1.0	7.48	86	6.03	17.0	1.20
1.28	1.0	7.48	85	6.40	16.0	.95
1.50	.9	6.74	84	6.90	14.0	.87
1.75	.9	6.74	84	8.10	12.0	.73
2.00	.6	4.49	85	9.09	20.0	.75
2.50	.9	6.74	86	10.50	18.0	.82
3.00	.8	5.98	84	12.00	20.0	.75
3.50	.9	6.74	84	13.50	19.0	.73
4.00	.9	6.74	85	14.50	21.0	.80
4.50	.7	5.24	87	16.00	20.0	.83
5.00	.8	5.98	85	18.00	18.0	.92
		SHUT DOWN OVER NITE				
5.00	.6	4.49	-	18.00	12.0	1.20
5.25	.5	3.74	-	18.00	-	-
		Remove Diaphragm, washed with Hexane				
0	-		-	-	33.0	-
.02	-		-	-	22.0	-
.09	2.1	15.70	-	2.50	-	.75
.17	1.0	7.48	78	1.70	-	1.50
.25	1.0	7.48	-	2.20	-	1.80
.33	1.0	7.48	78	2.70	25.0	2.00
.50	1.0	7.48	78	3.30	18.0	2.40
.75	1.0	7.48	80	3.50	17.0	2.75
1.00	1.0	7.48	80	3.90	21.0	3.40
1.25	1.0	7.48	80	4.10	19.0	3.60
1.75	1.0	7.48	79	4.20	19.0	3.60
2.25	1.0	7.48	79	4.20	21.0	3.50
2.75	1.0	7.48	79	4.20	20.0	3.60
3.25	1.0	7.48	78	4.20	18.0	3.10
3.75	1.0	7.48	78	4.20	18.0	3.10
3.75	1.0	7.48	79	4.50	18.0	2.80
5.00	1.0	7.48	79	4.80	18.0	1.50
5.75	1.0	7.48	80	4.90	20.0	1.20
6.75	1.0	7.48	78	5.00	20.0	0.86
7.75	1.0	7.48	78	5.00	21.0	0.75

TABLE 22 (Continued)

8.75	1.0	7.48	80	5.50	22.0	0.63
9.75	1.0	7.48	78	5.80	22.0	0.56
10.75	1.0	7.48	79	6.00	22.0	0.50
11.75	1.0	7.48	80	6.30	21.0	0.52
20.25	0.5	3.74	-	6.00	-	-
20.50	1.0	7.48	79	11.40	27.0	0.38
24.00	1.0	7.48	81	12.50	29.0	0.48
28.00	1.0	7.48	82	18.50	30.0	0.50
	Regeneration with Water					
0	0.03	0.23	58	17.50	-	-
1.75	0.03	0.23	-	17.50	-	-
	Treated with Hexane without drying					
0	0.0	0.00	61	17.50	-	-
	Regenerated with Methanol					
0	-	-	61	-	-	-
2.00	-	-	60	3.50	-	-
3.50	0.70	5.24	60	4.00	-	-
3.75	4.50	33.60	60	14.00	-	-
4.30	3.00	22.4	60	14.50	-	-

* By Hach turbidimeter

diaphragm. After the second ΔP buildup the diaphragm was regenerated with methanol. These preliminary tests on regeneration involved removing the diaphragm from this cell rather than in situ treatment.

Stabilization Tests-Discussion

The present results are very preliminary but indicate that the 3.2μ fiber bed can be stabilized by cementing together with a resin. Furthermore, using a methacrylate resin which contains numerous polar groups, the coalescence efficiency remains the same 100% as the original commerically available fibers with some type of bakelite coating.

There are numerous possibilities open in this type of stabilization work. The most desirable would be to use such a resin that is more oleophilic or non polar in nature. This might result in the pressure drop building up to some constant value so that regeneration is not necessary. Regeneration techniques should involve in situ methods. This should be no problem. In addition, regeneration using steam or air rather than solvents would have considerable advantages.

SECTION X

ACKNOWLEDGEMENT

This work was carried out at the Illinois Institute of Technology under the dircction of Dr. W.M. Langdon and Dr. D.T. Wasan. The bulk of the experimental work was carried out by Mr. P. Naik. Messrs. K. Nelson, G. Ramsey, S. Browning, L. Ksycki, L. Gupta and M.B. Ranade also participated in the experimental program. Photographs of equipment were taken by Mr. Brian Swanson.

Industrial effluent material for testing was supplied by Interlake Steel Corporation, Riverdale, Illinois. The large scale cell was supplied by Ickes Braun Glass Company, Aplakisic, Illinois. Teflon screen material for the second stage was supplied by General Steel Tank Company of Reedsville, North Carolina.

We wish to acknowledge the many helpful suggestions provided by Dr. R.C. Kintner and Dr. B.S. Swanson, Illinois Institute of Technology.

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SECTION XI

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SECTION XII

GLOSSARY

Coalescence Efficiency - Percentage of inlet oil removed by coalescence.

Diaphragm - Active section of the coalescer bed.

FPT - Female pipe thread.

Holdup - The volume of dispersed phase retained by the bed per volume of fibers.

ILS - Interlake Steel Corporation.

IPS - International pipe size

Oil Removal Efficiency - Percentage of inlet oil removed by the coalescer bed.

TFE - Teflon.

TU - Turbidity unit.

SECTION XIII

SYMBOLS

K_o	Permeability, $cm.^2$
V	Superficial velocity, cm./sec.
L	Bed length, cm.
μ	Unit of length, micron (1 micron = 1×10^{-4} cm.)
μ_c	Viscosity of the continuous phase, gm./cm.sec.
μ_d	Viscosity of the dispersed phase, gm./cm.sec.
ρ_d	Density of the dispersed phase, $gm./cm.^3$
σ_{12}	Interfacial tension, dynes/cm.

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1 Accession Number	2 Subject Field & Group	SELECTED WATER RESOURCES ABSTRACTS INPUT TRANSACTION FORM
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Illinois Institute of Technology
Chicago, Illinois 60616

6 Title

Experimental Evaluation of Fibrous Bed Coalescers for Separating Oil-Water Emulsions

10 Author(s)

W.M. Langdon and
D.T. Wasan

16 Project Designation

Project No. 12050 DRC

21 Note

22 Citation

23 Descriptors (Starred First)

*Dispersed Oil Removal from Water

25 Identifiers (Starred First)

*Fibrous Bed Coalescers, *Phenol Formaldehyde Coated Fiber Glass Fibers, Teflon Coated Screen, Kerosene, #30 Lubricating Oil

27 Abstract A 1 sq. ft. coalescer unit using filter press construction has been designed for removing dispersed oil from water and tested on both a synthetic stream and on an actual pollutant stream. The oil removal efficiency was essentially 100% at a superficial velocity of 1 fpm. The pressure drop increased from 3 to 25 psi over run times which varied from 13 hrs. to 294 hrs., due to both accumulation of oil in the bed and mechanical degradation of the fibers. Preliminary tests indicated that the bed degradation phenomenon could be eliminated by structurally stabilizing the compressed fibers with methacrylate resin. Such fiber beds could be regenerated by various solvent treatments and reused.

The performance of fiber glass coalescers was studied in depth using a cell with an active area of 1.77 sq. in. The commercial fibers, with phenol formaldehyde coatings and a fiber diameter of 3.3μ gave efficiencies of 90-99% with bed densities of 12 lb./ft.^{3} when operating at superficial velocities from 0.2 to 4 fpm on emulsions containing 50-500 ppm of oil. The present design is suitable for large scale operation by the use of both multiple cells and larger individual cells. It is estimated that operating costs on the order of 0.13 \$/10^3 gal. are involved for the worst case of single use of fiber. If the fibers can be regenerated operating costs would be reduced to 0.01 \$/10^3 gal.

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